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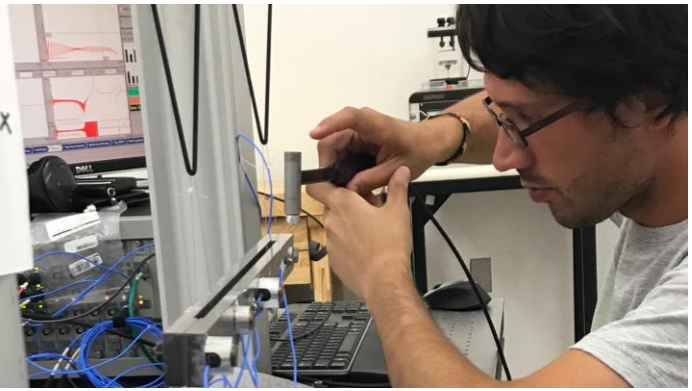
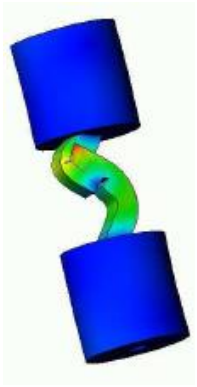
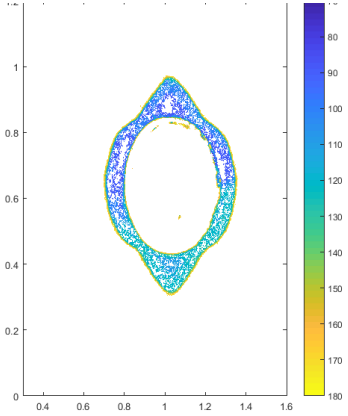


N=O=MAD





Experimental Characterization of a New Benchmark Structure to Predict Damping Nonlinearities

Aabhas Singh, Matteo Scapolan, Yuta Saito

U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration

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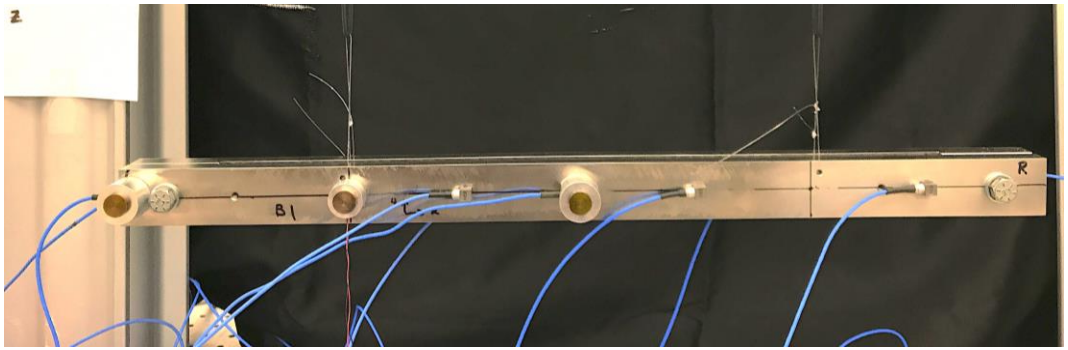
Agenda



1. Introduction
2. Project Overview
3. Joint Characterization
4. Experimental Methodology
5. Nonlinear Parameter Characterization
6. Conclusion

Research Team

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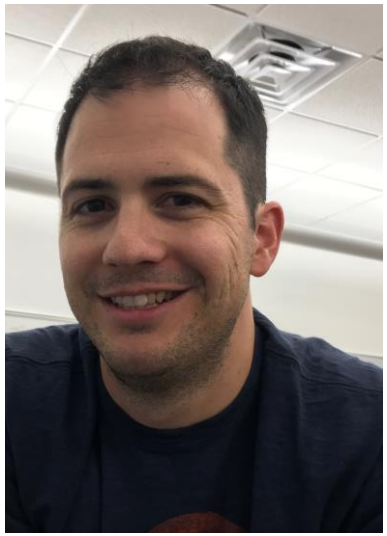
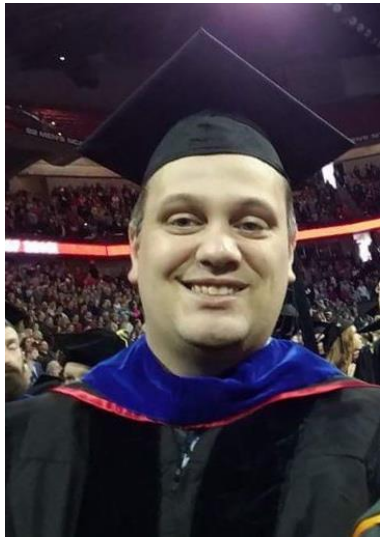


Ben Pacini

Sandia National Laboratories

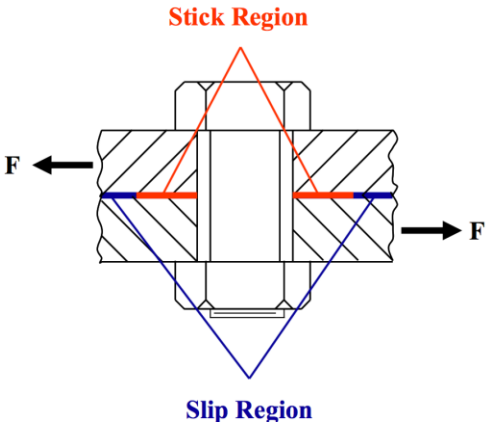
Dan Roettgen

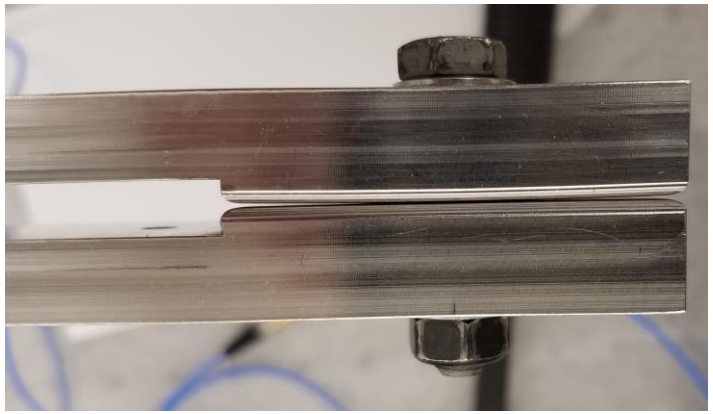
Sandia National Laboratories



Motivation

- Finite element models (FEMs) of interfaced structures leads to large uncertainties
  - Introduce nonlinearities
  - Difficult to predict stiffness and damping at the interface
- Bolted structures
  - Well tightened bolts still exhibit regions of slip at the edge of contact
    - Introduces hysteresis and an increase in damping

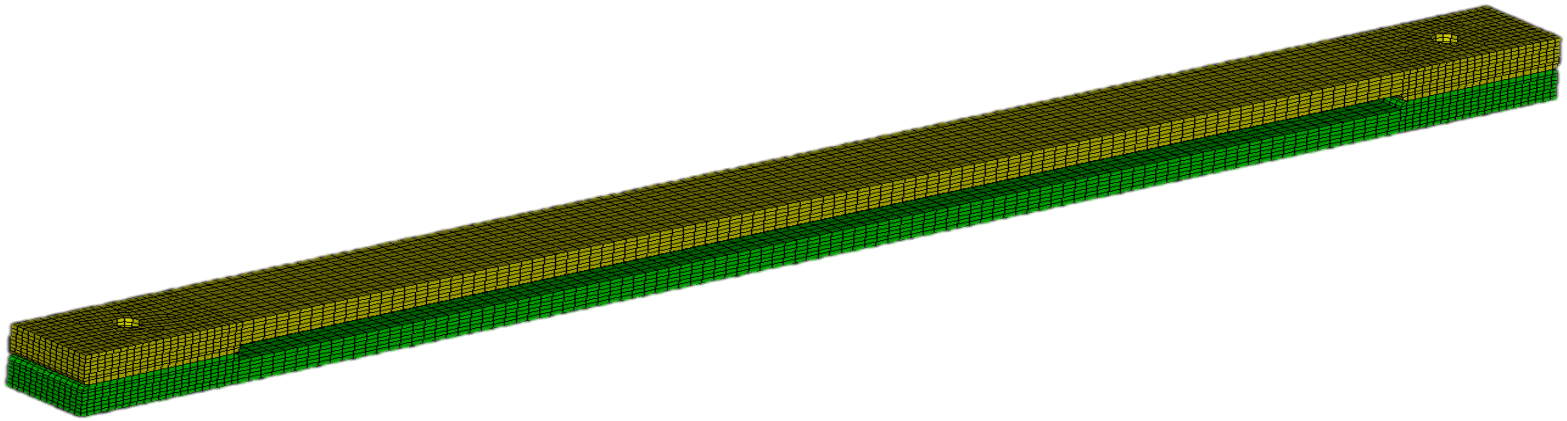




Project Overview

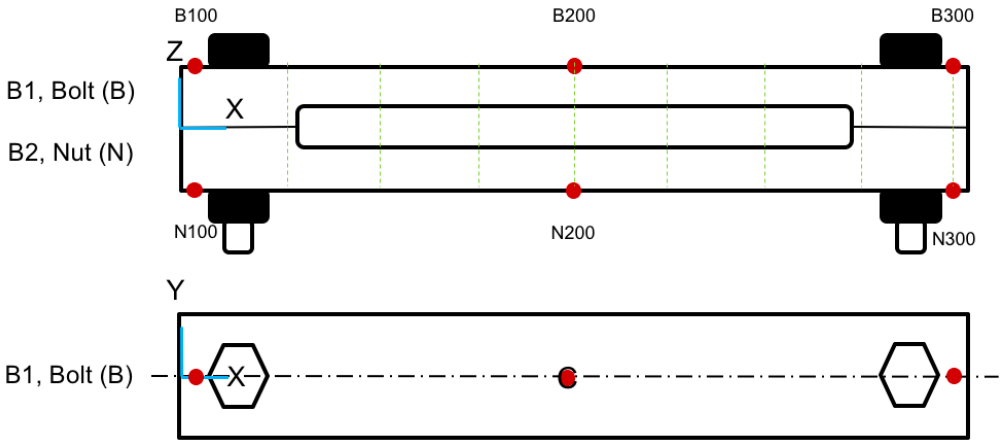
- Experimentally characterize a new benchmark structure
  - Designed such that the nonlinearities can be predicted with current simulation tools
  - Identify the degree of nonlinearity
  - Identify modes of interest

- Measure modal parameters as a function of amplitude
  - Help understand why predictive simulations are incorrect and begin to improve those methods



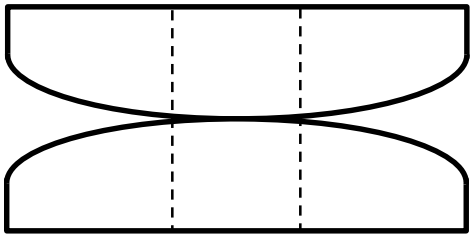
Benchmark Structure – S4 Beam (S4B*)

- Stainless Steel – 304
- Two bolted interfaces
- Four contact surfaces
- Reference points spacing every 2.5” for the 20” Beam



*Sandia – Singh – Scapolan – Saito (S4) Beam

S4B Variations

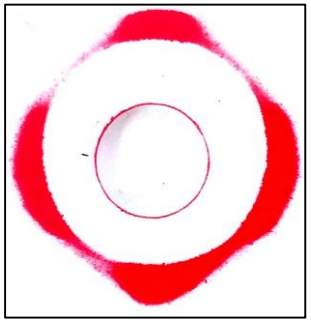


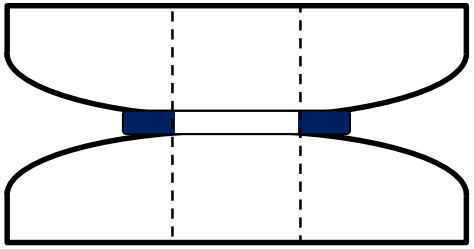
B1B2

Curved – Curved Interface

B5B6

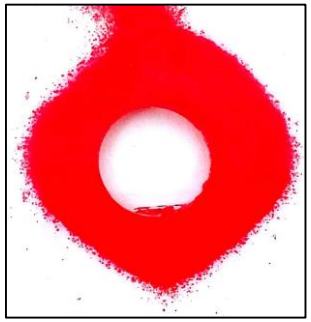
Flat – Flat Interface

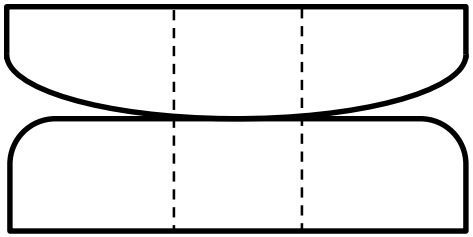




B1B2W

Curved – Curved Interface with SS Washer



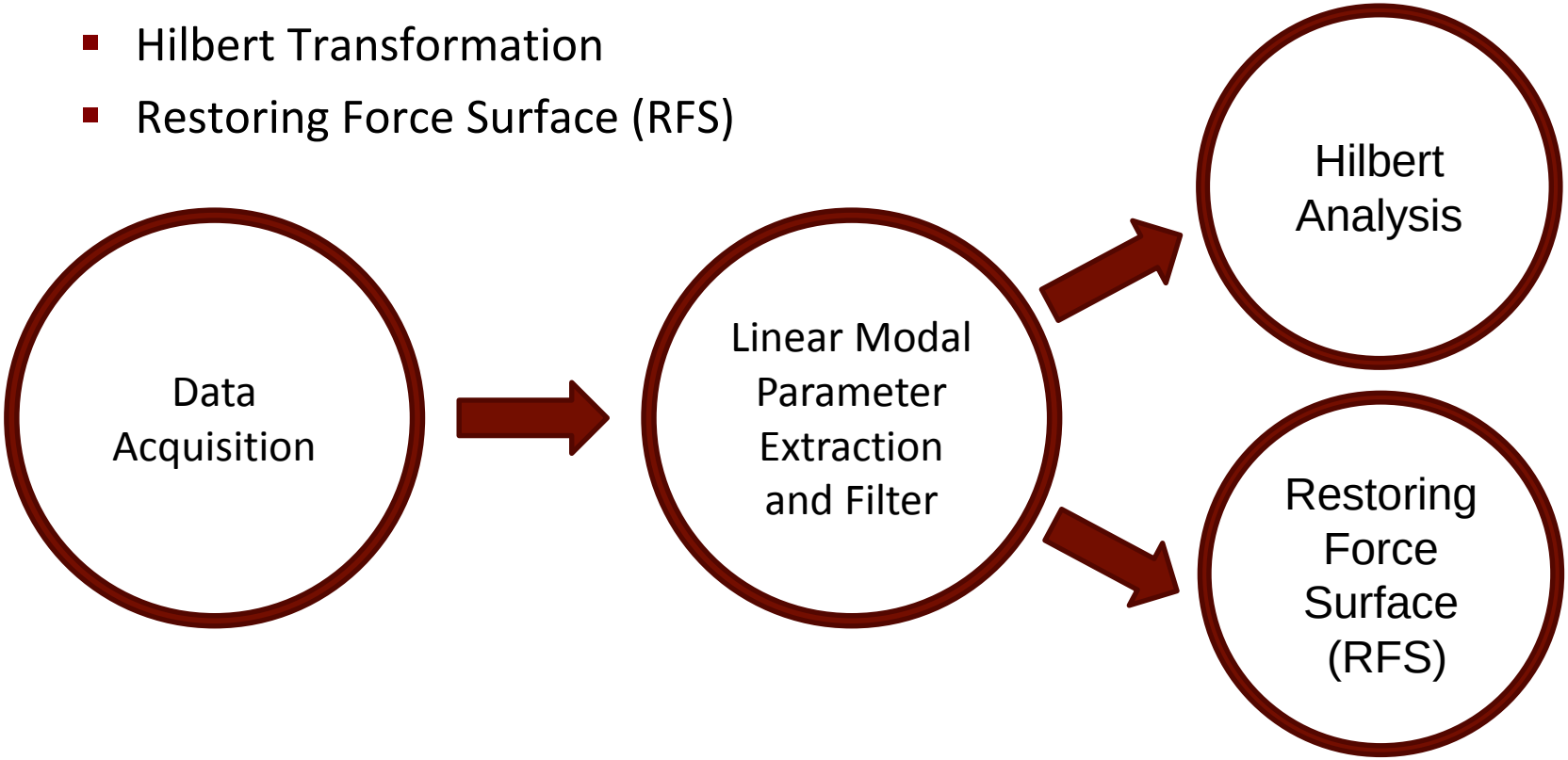


B1B6

Curved – Flat Interface

S4B Characterization Methodology

- Characterize joint through pressure analysis
- Characterize degree of linearity
- Characterize nonlinear parameters through
  - Hilbert Transformation
  - Restoring Force Surface (RFS)



Joint Characterization

Objective:
Have to find some way to “characterize’’ the joint to link the variance in the torque/contact surfaces to the change in the structural response (FRF)

In reality, the contact surfaces look like…

Flat

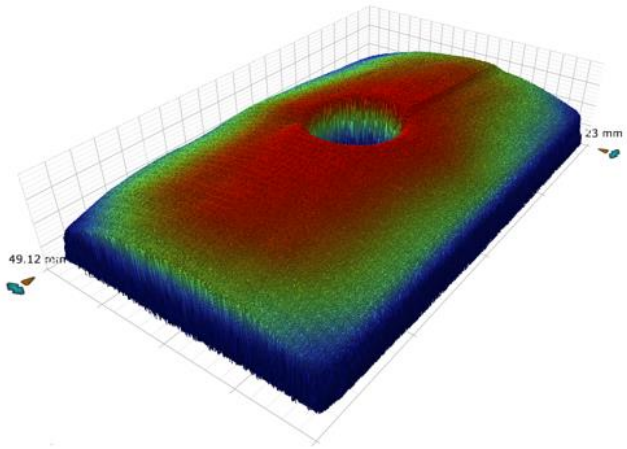
Curved

Not flat nor curved

Take measurements of the contact surfaces to characterize the joints

Digital Imagery

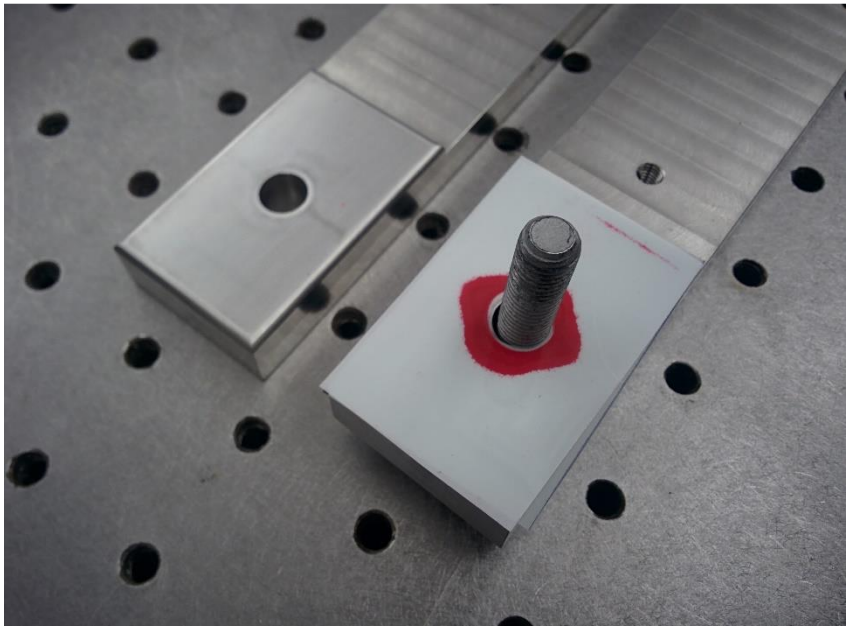
Use a high resolution optical camera to obtain the three-dimensional profiles measuring nm (nano-meter) resolution.

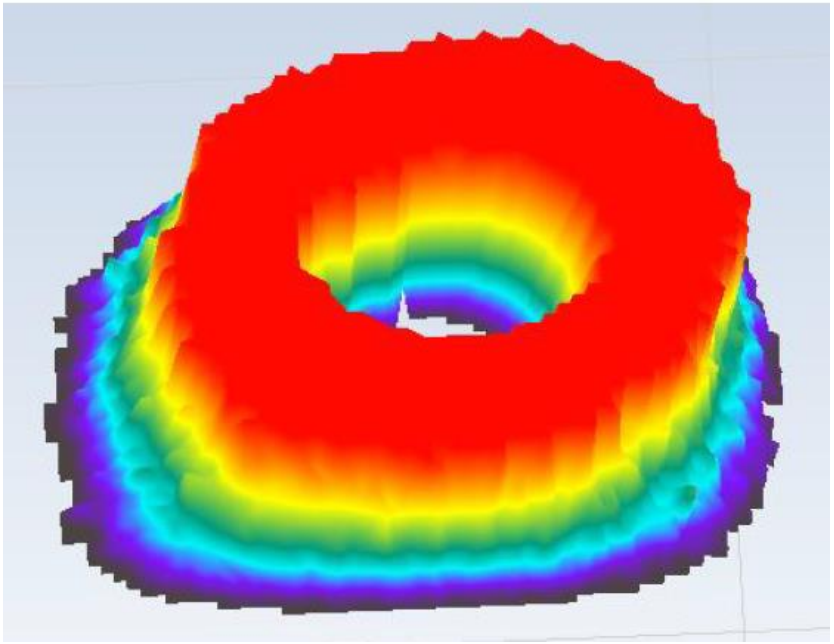


Result:
Extract surface roughness parameters (fractal dimension and fractal roughness parameter) and true geometry

Pressure film

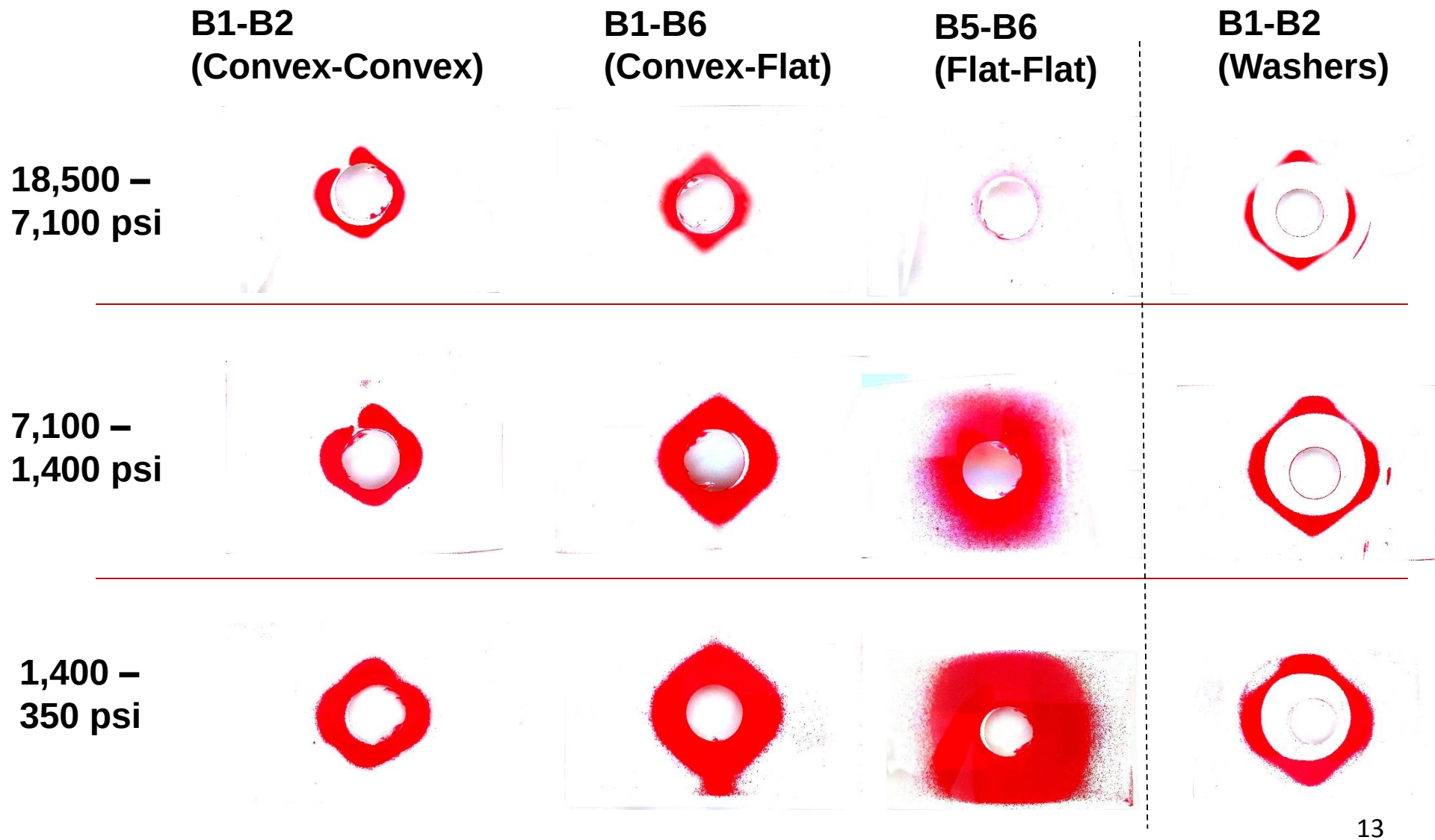
Use pressure films to extract the pressure along the surface of the interface for different torque levels.



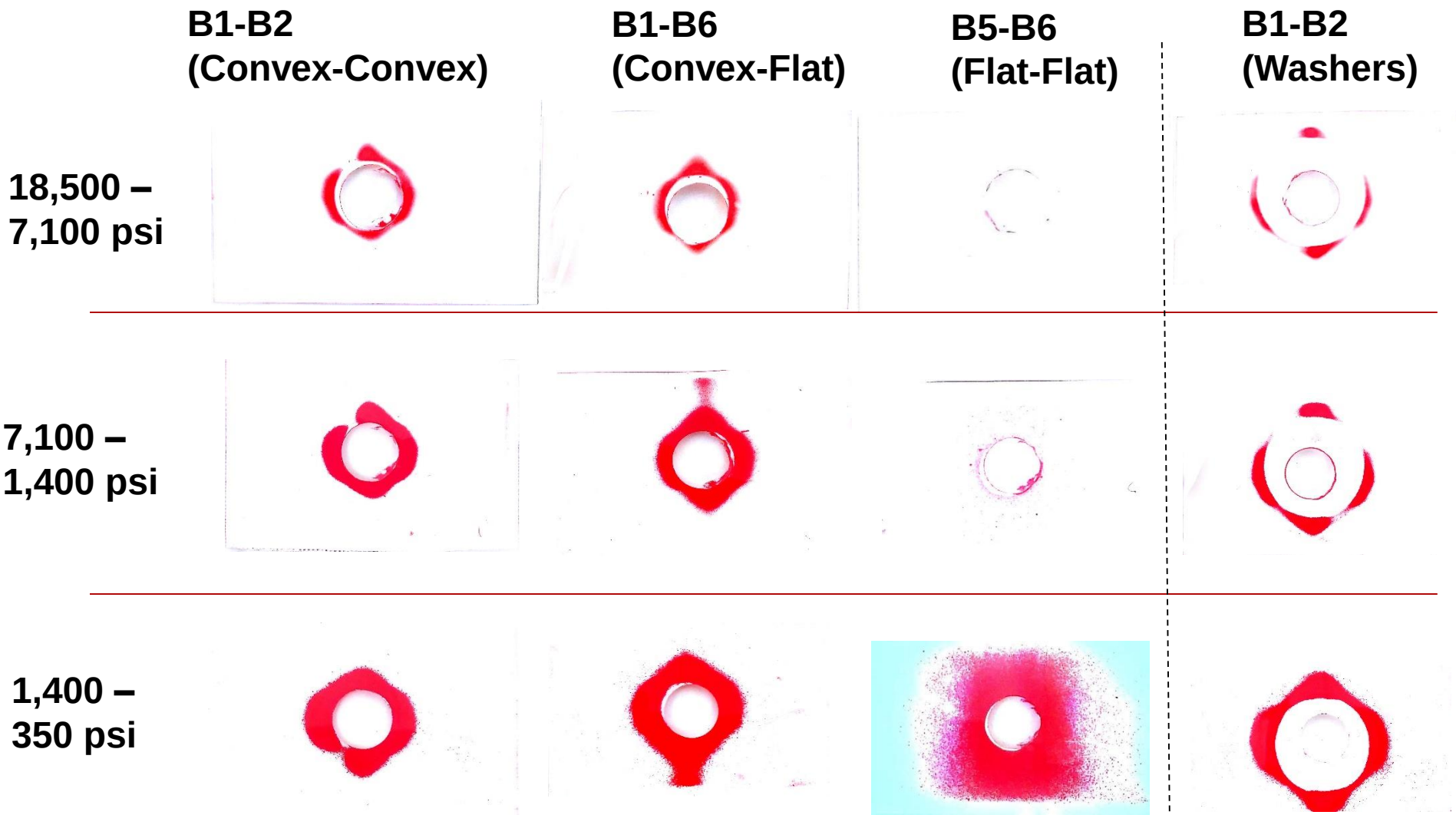


Result:
Extract the contact area and the normal/tangential force acting at different torque levels and combination of contact surfaces.

Pressure Films (high torque)



Pressure Films (low torque)



Putting it together

Pressure films

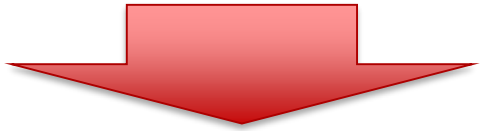
- Find the pressure along the contact surface + surface area of contact
- Compute the contact area, normal/tangential force

Digital Imagery

- Find the high resolution surface contour
- Compute the surface roughness parameters

Material Characteristics

- Elastic moduli, hardness, mass. etc



Find the “truncated area” i.e. the area of the contact after deformation in the interface

Compute the normal/tangential stiffness and damping of the joint (eventually)

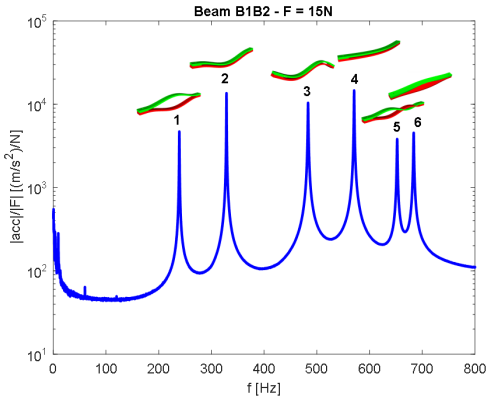
Experiment Design

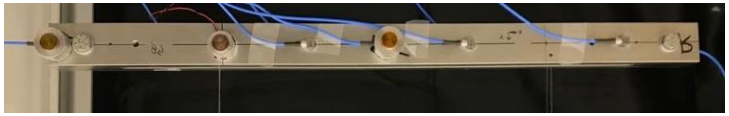
Linear modes identification

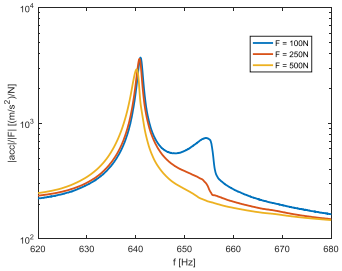
Optimal experimental setup

Nonlinear modes evaluation

Nonlinear time histories







	Input Force			
Torque Levels	15 N	100 N	250 N	500 N
10.2 Nm	X	X	X	X
16.9 Nm	X	X	X	X
25.1 Nm	X	X	X	X

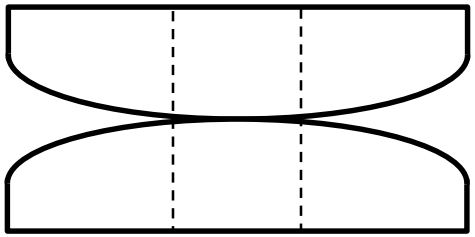
Experiment Design

Nonlinear

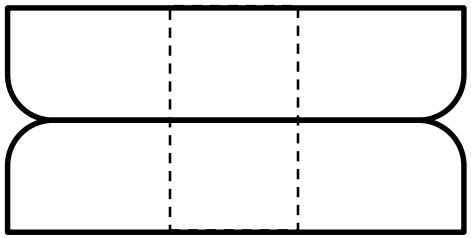
Nonlinear

Torque Levels	Input Force				
		15 N	100 N	250 N	500 N
	10.2 Nm	X	X	X	X
	16.9 Nm	X	X	X	X
	25.1 Nm	X	X	X	X

- 3 torque levels
- 4 force levels
- 4 interfaces

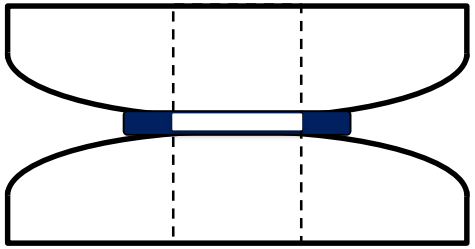


B1B2

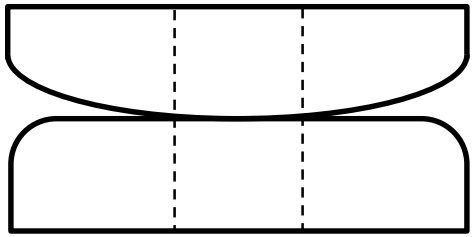


B5B6

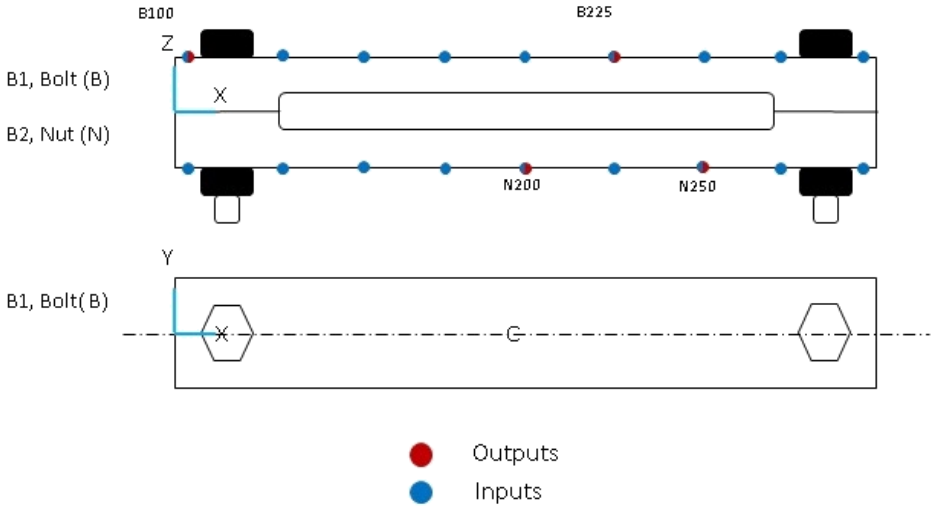
B1B2W

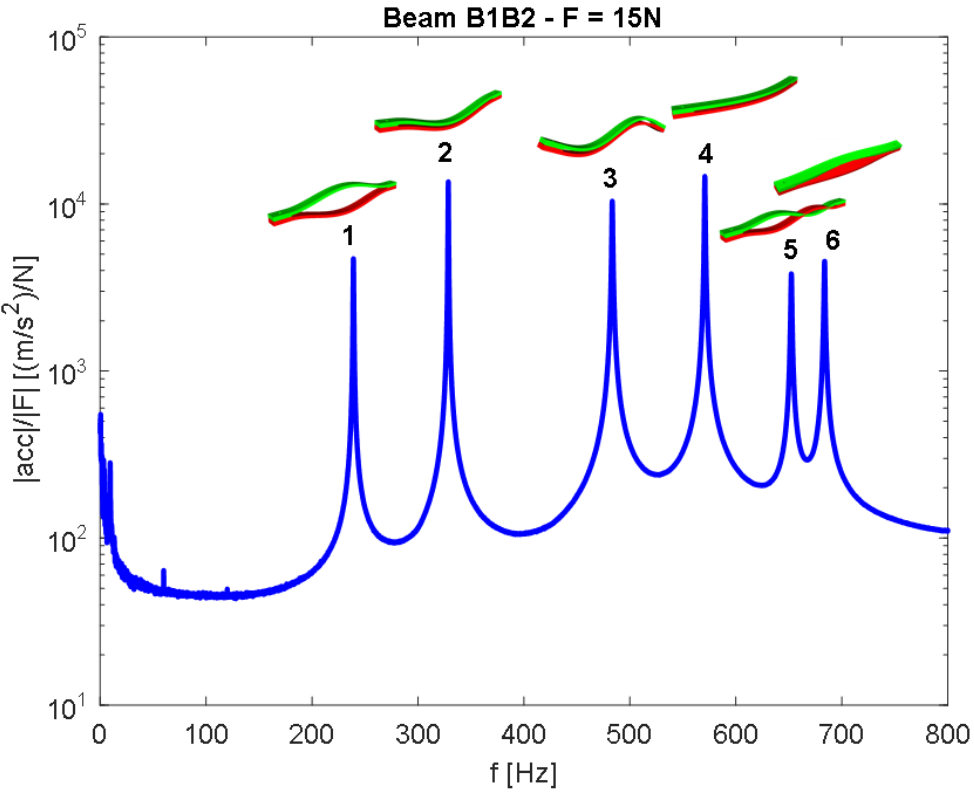


B1B6



Linear Modeshapes Identification



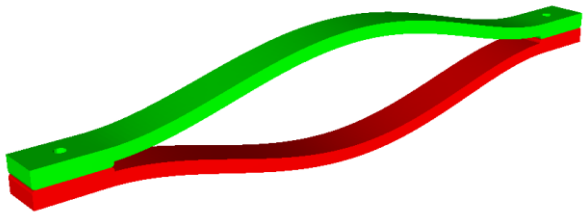


- Roving Hammer
- Minimum number of accelerometers
- Low amplitude impact

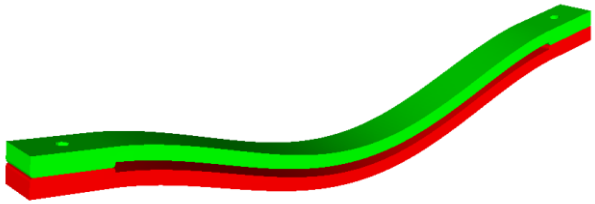
Linear Modeshapes

Modeshapes

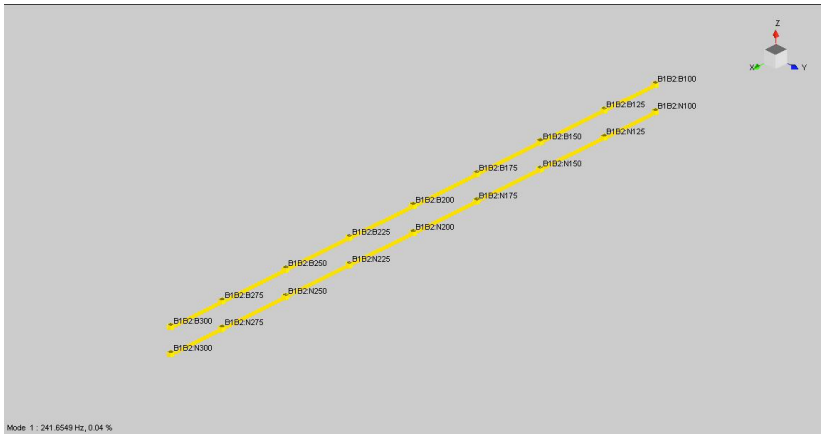
Mode 1
f_n = 241.89 Hz, ζ = 0.00024



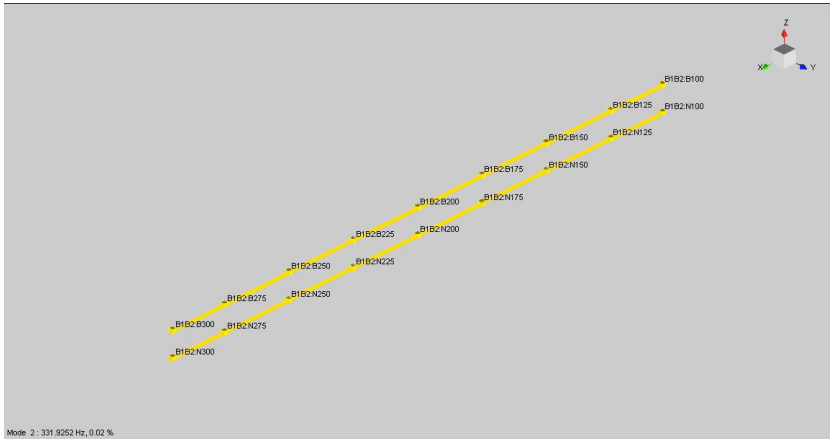
Mode 2
f_n = 332.09 Hz, ζ = 0.00012



Opening mode



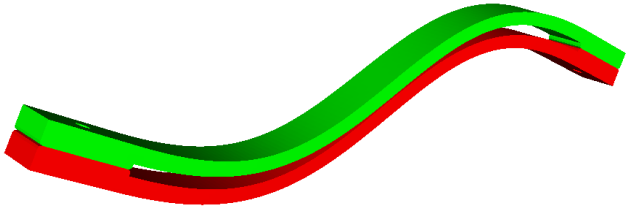
First z bending, out of phase

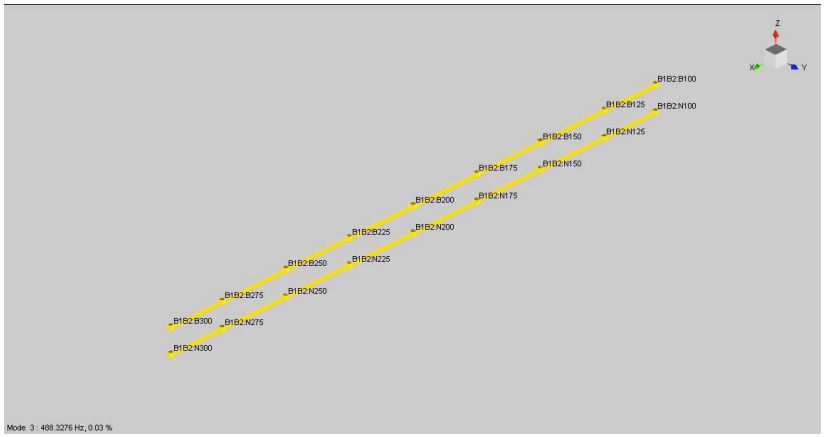


First z bending, in phase

Modeshapes

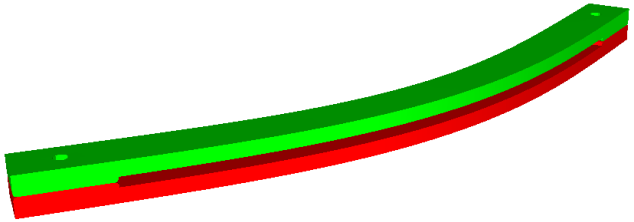
Mode 3
f_n = 488.76 Hz, ζ = 0.00028

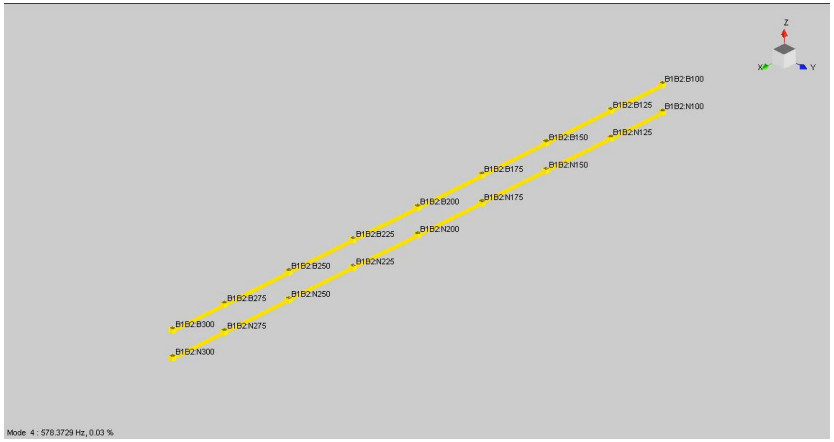




Second z bending, in phase

Mode 4
f_n = 578.24 Hz, ζ = 0.00031

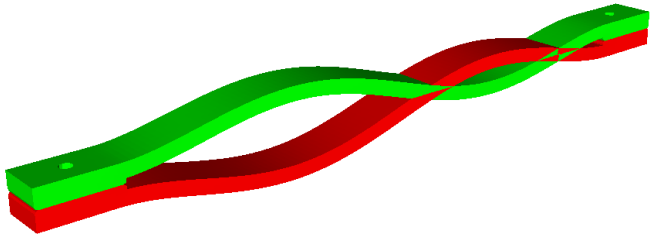




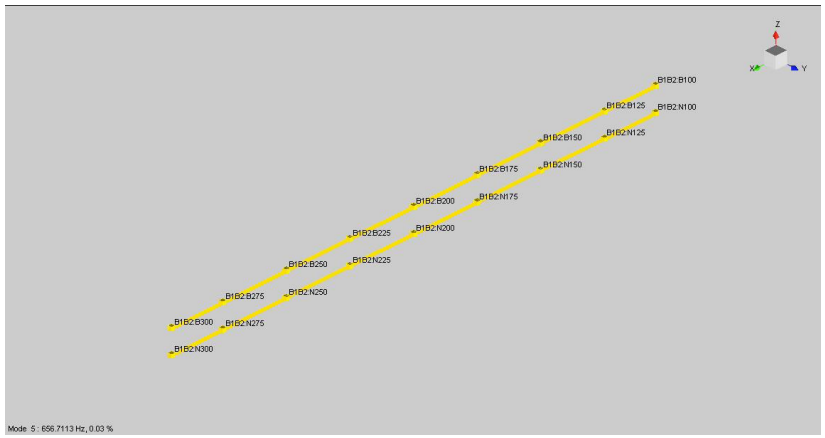
First y bending, in phase

Modeshapes

Mode 5
f_n = 657.38 Hz, ζ = 0.00021

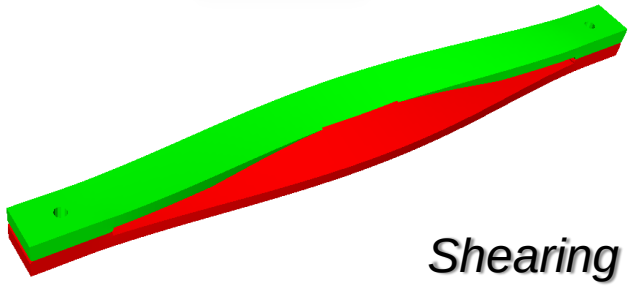


Opening mode

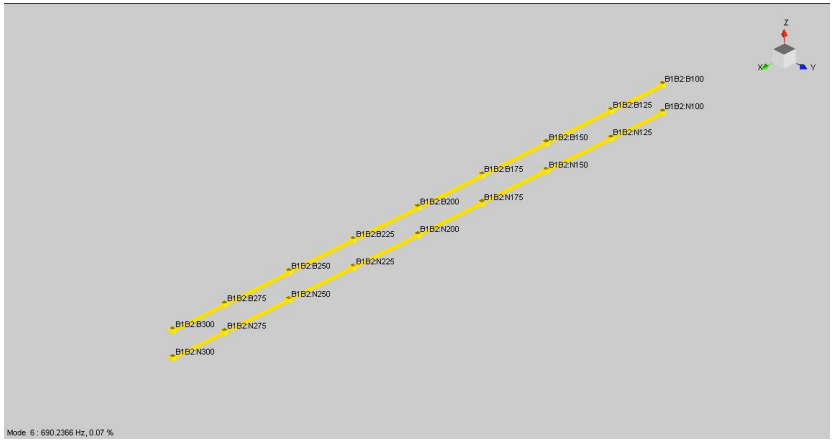


Second z bending, out of phase

Mode 6
f_n = 689.95 Hz, ζ = 0.00071



Shearing mode

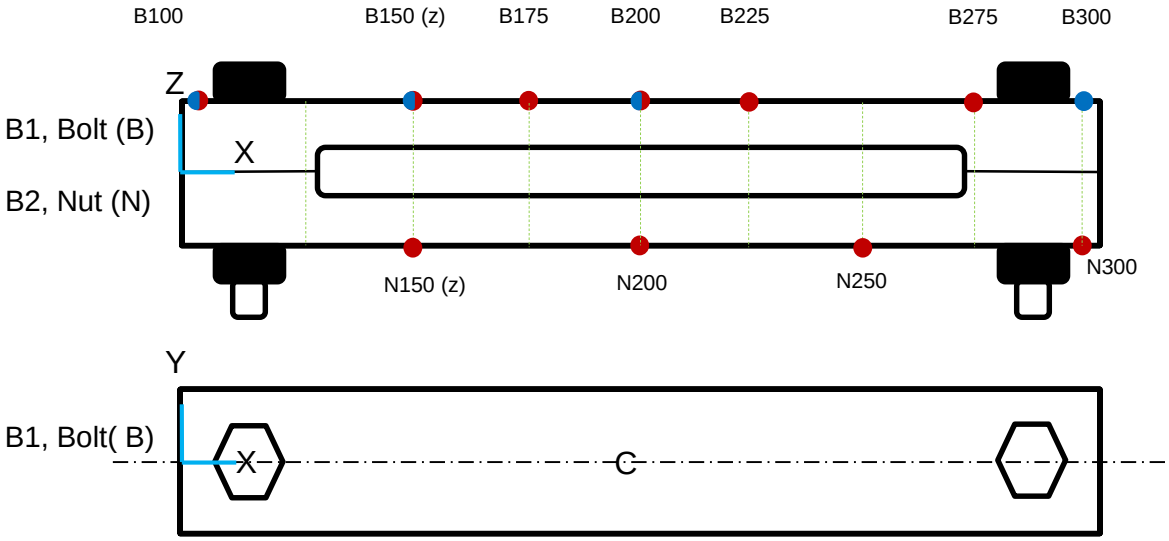


First y bending, out of phase

Experimental Setup

7 input – 28 output setup

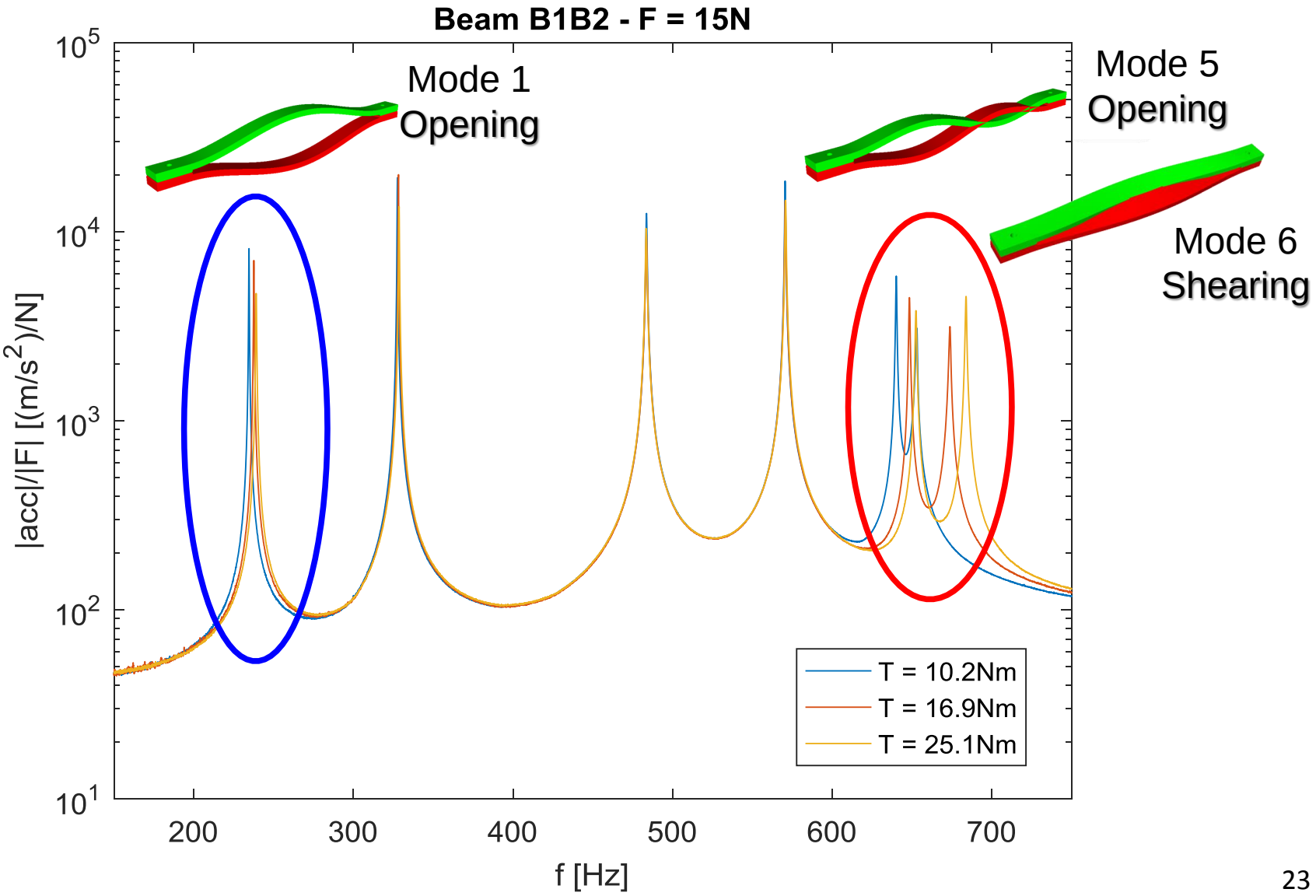
- Outputs:
  - Triaxials (X,Y,Z)
    - B200, N200
    - B100, N300
    - B175, B225, B275
    - N150, N250
  - Uniaxials (Z)
    - B150
- Inputs:
  - B300 z,y
  - B200 z,y
  - B100 z,y
  - B150 z



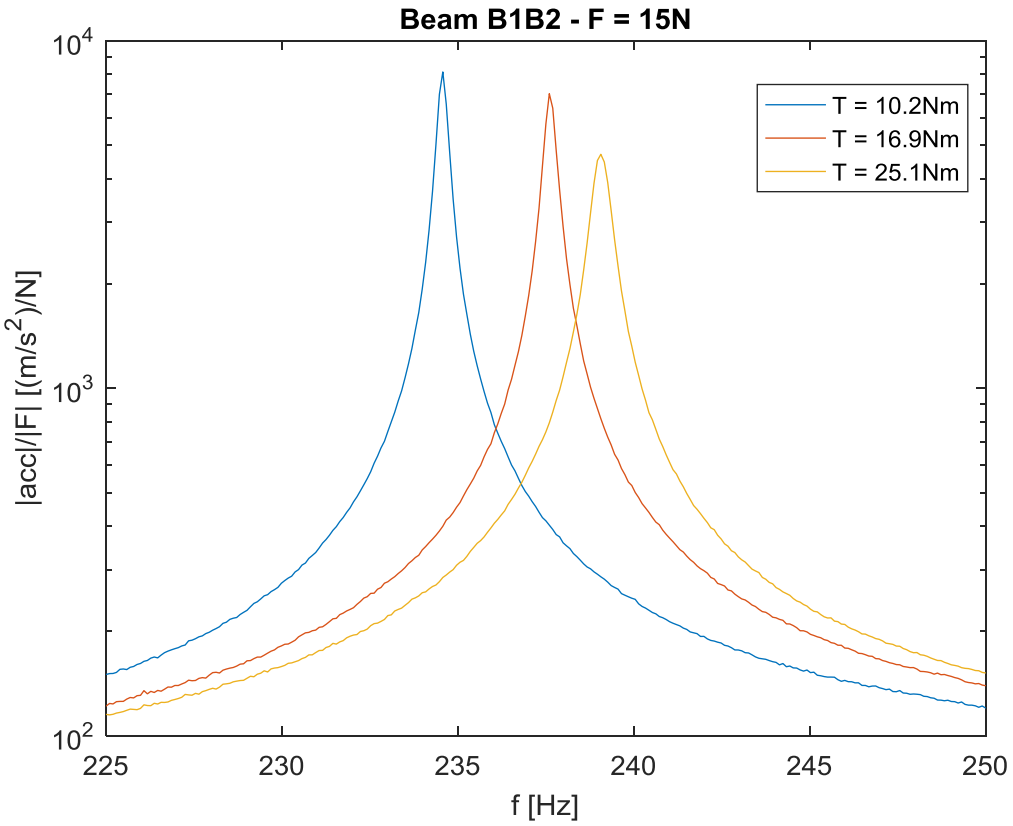
- 10 sensors
- 28 Channels (19 without X)
- 7 input points

Nonlinear analysis and time histories

Torque Effect

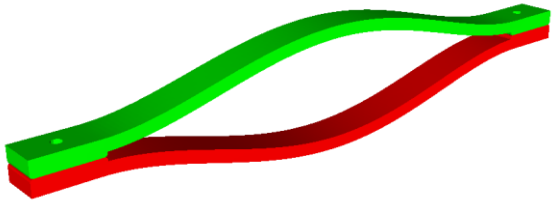


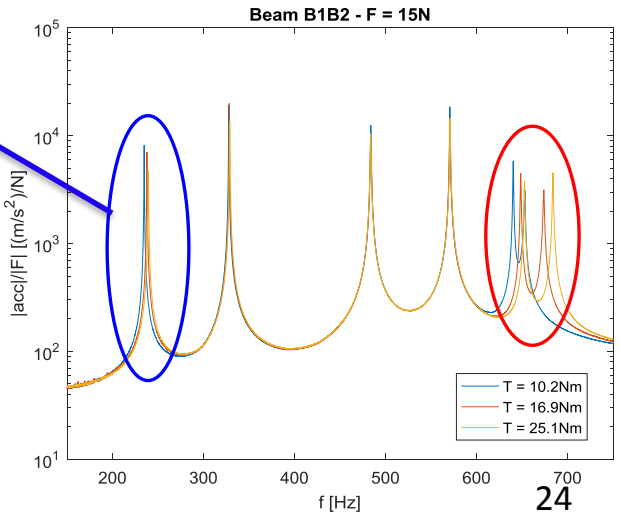
Torque Effect



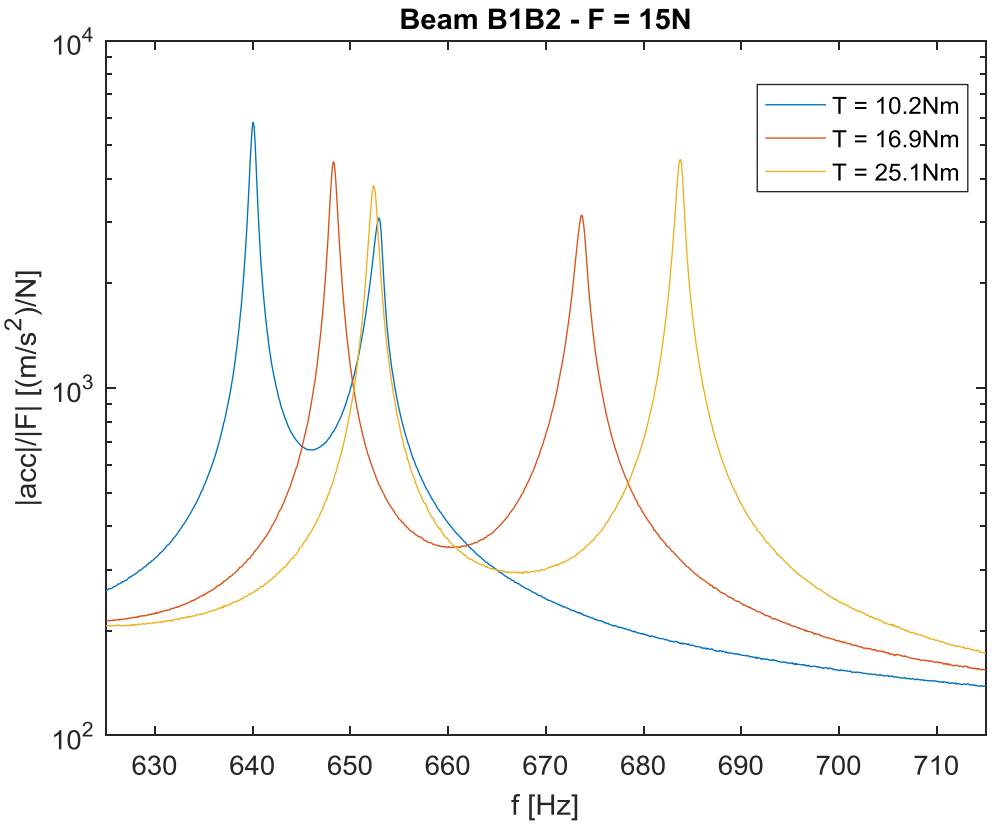
Frequency shift of **Mode 1**:

234.6 Hz → 239.1 Hz

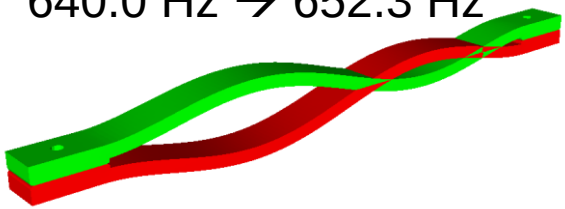




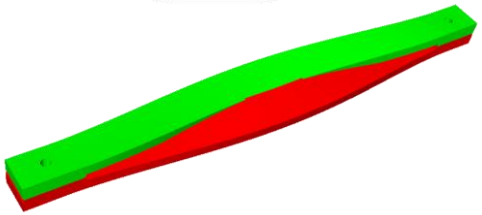
Torque Effect

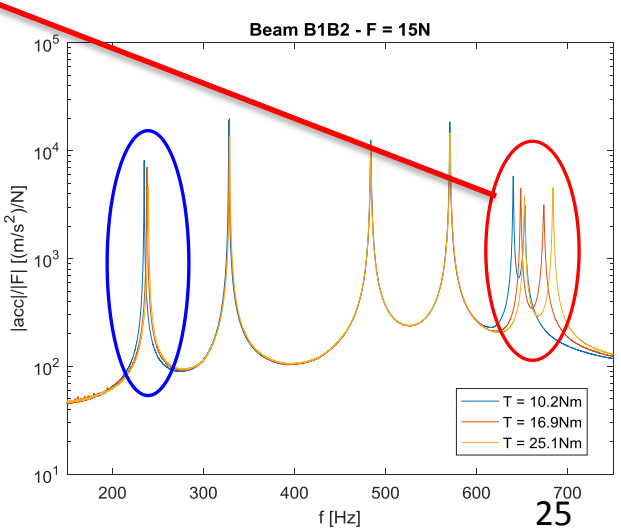


Frequency shift of **Mode 5**
640.0 Hz → 652.3 Hz

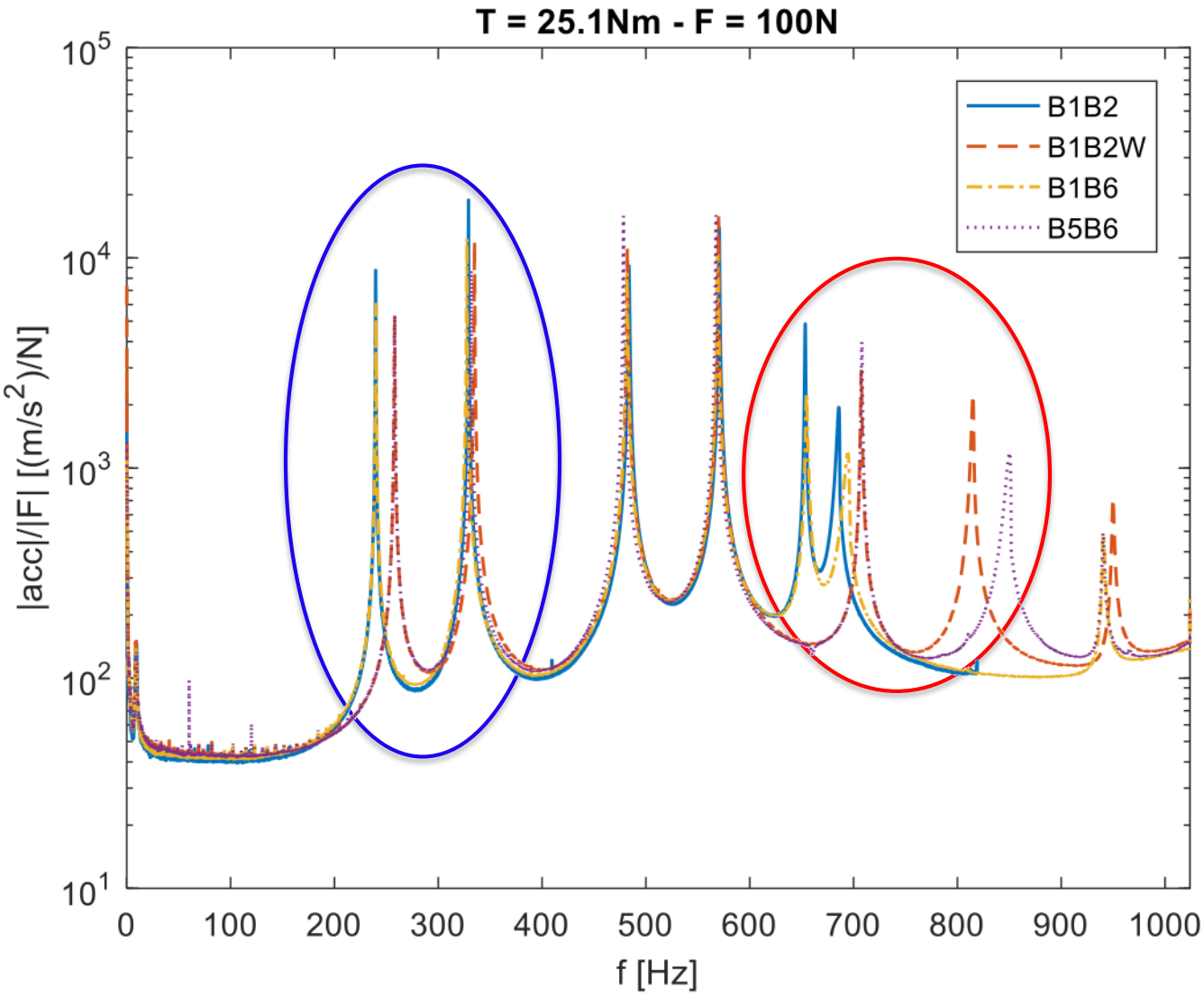


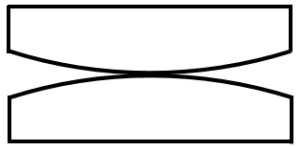
Frequency shift of **Mode 6**
652.9 Hz → 683.8 Hz



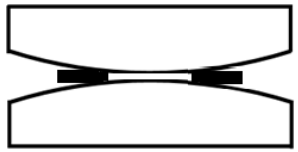


Beams Comparison



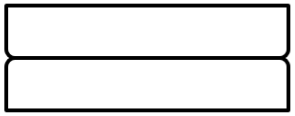


B1B2



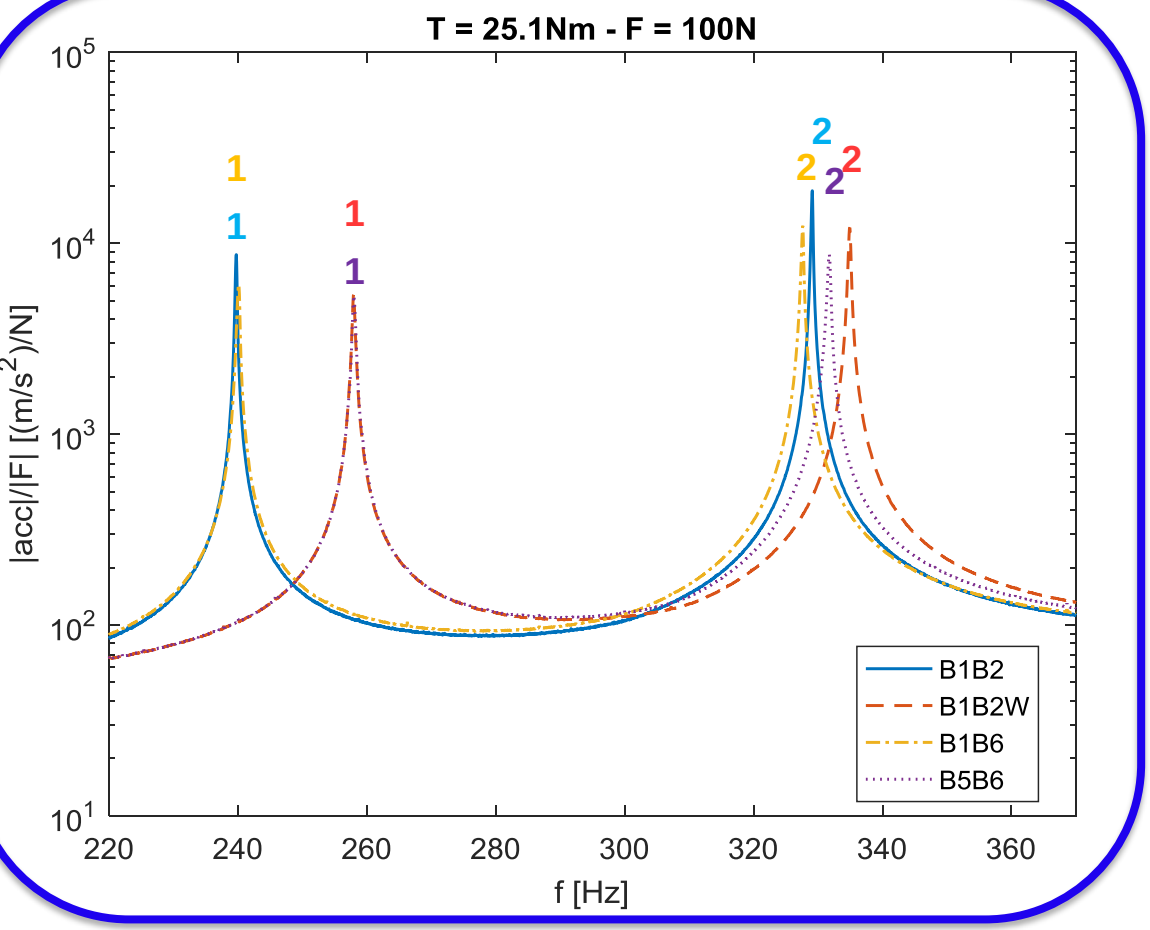
B1B2W

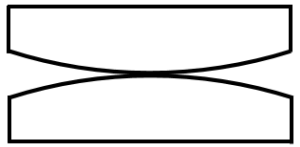
B1B6



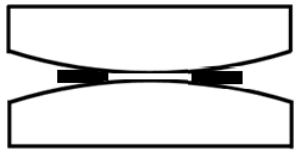
B5B6

Beams Comparison



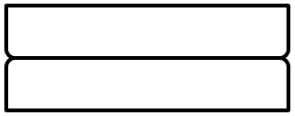


B1B2



B1B2W

B1B6

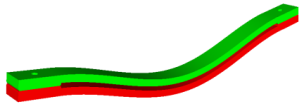


B5B6

Mode 1:

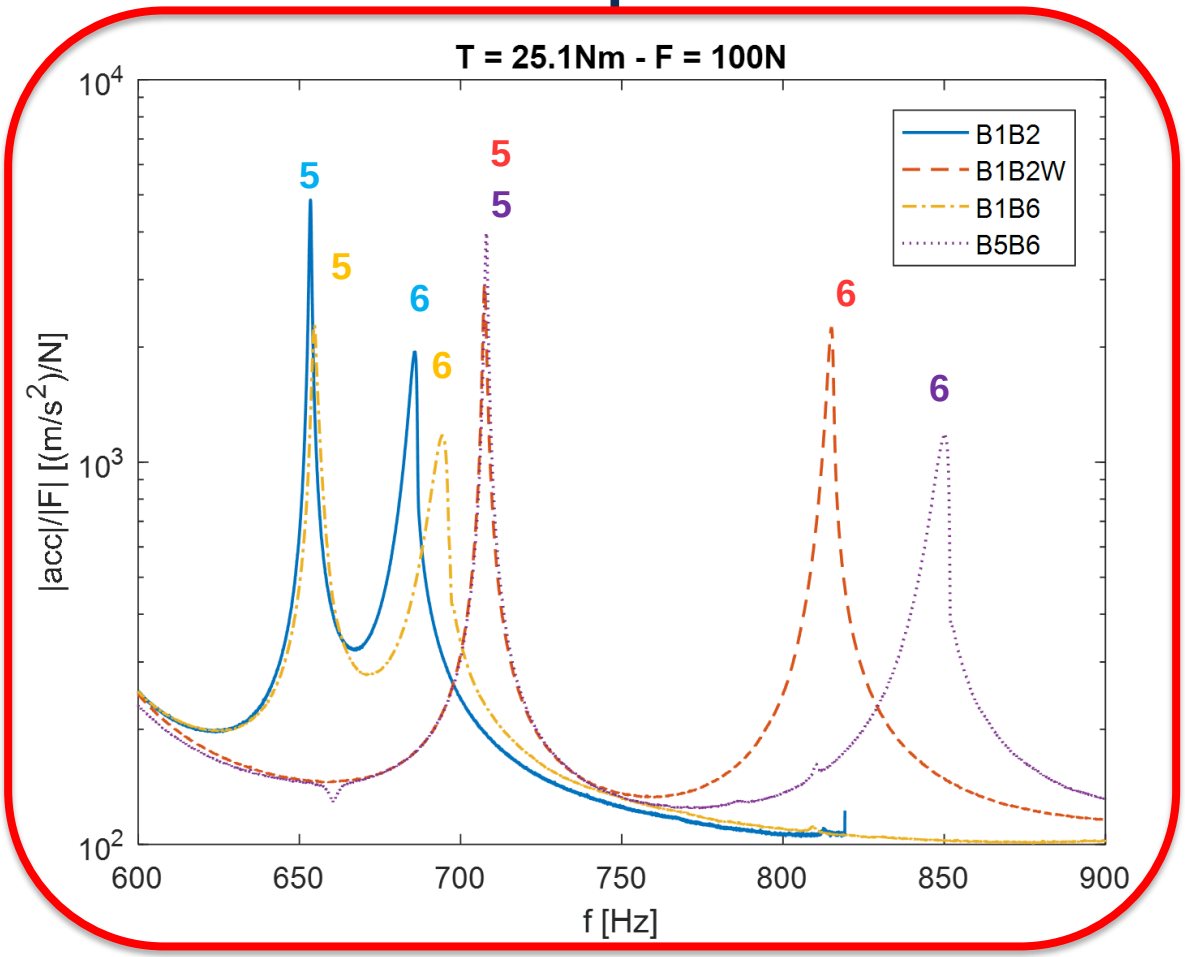
- **B1B2** & **B1B6** ~240 Hz
- **B1B2W** & **B5B6** ~258 Hz

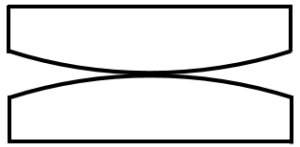
Mode 2:



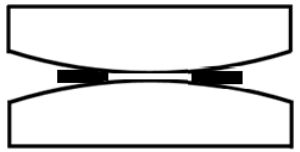
- **B1B2**, **B1B2W**, **B1B6** & **B5B6** [328 – 335] Hz

Beams Comparison



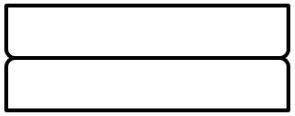


B1B2



B1B2W

B1B6

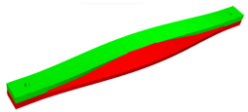


B5B6

Mode 5:

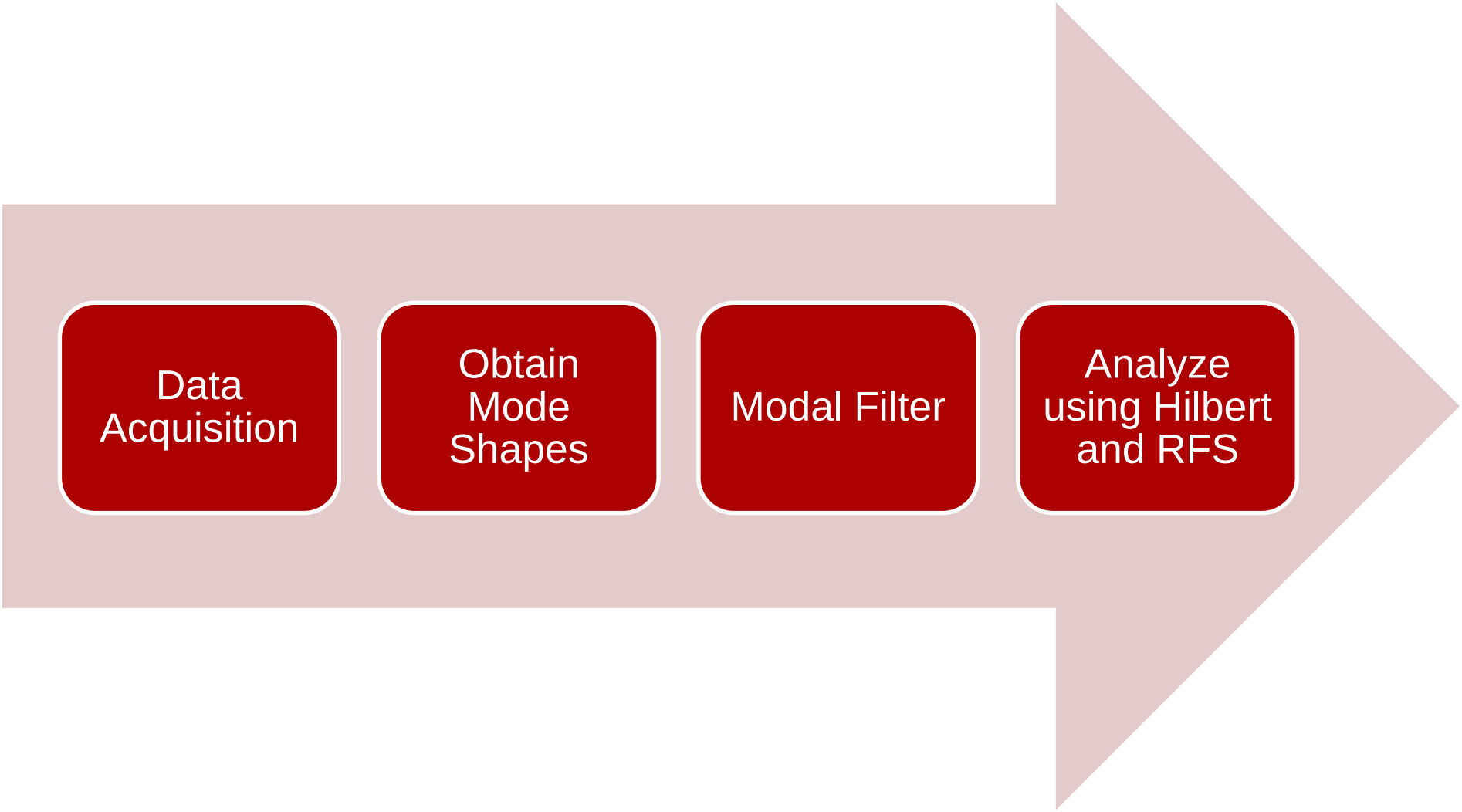
- B1B2 & B1B6 ~654 Hz
- B1B2W & B5B6 ~707 Hz

Mode 6:

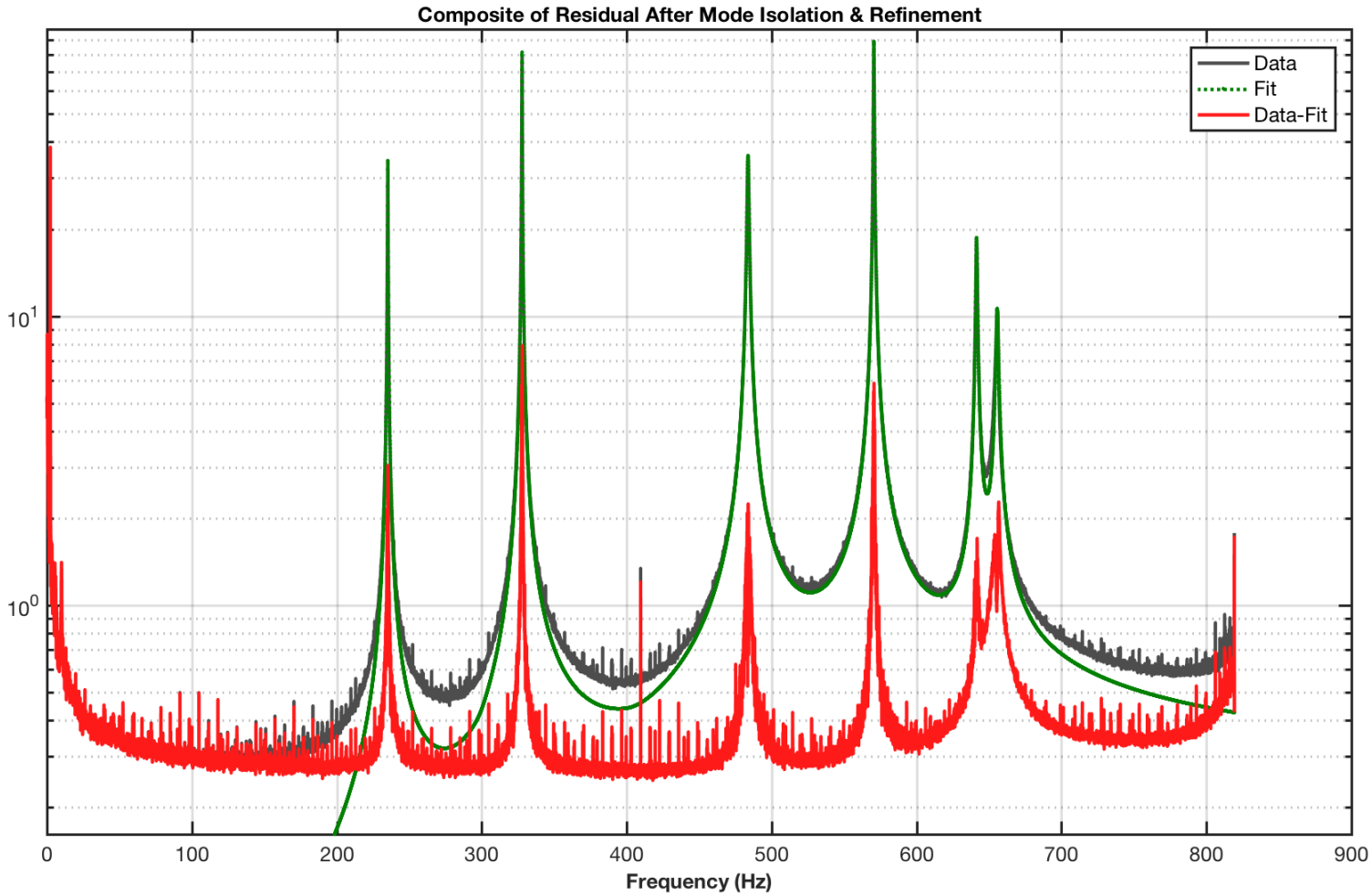


- B1B2 & B1B6 [685 - 695] Hz
- B1B2W & B5B6 [815 - 850] Hz

Numerical Analysis



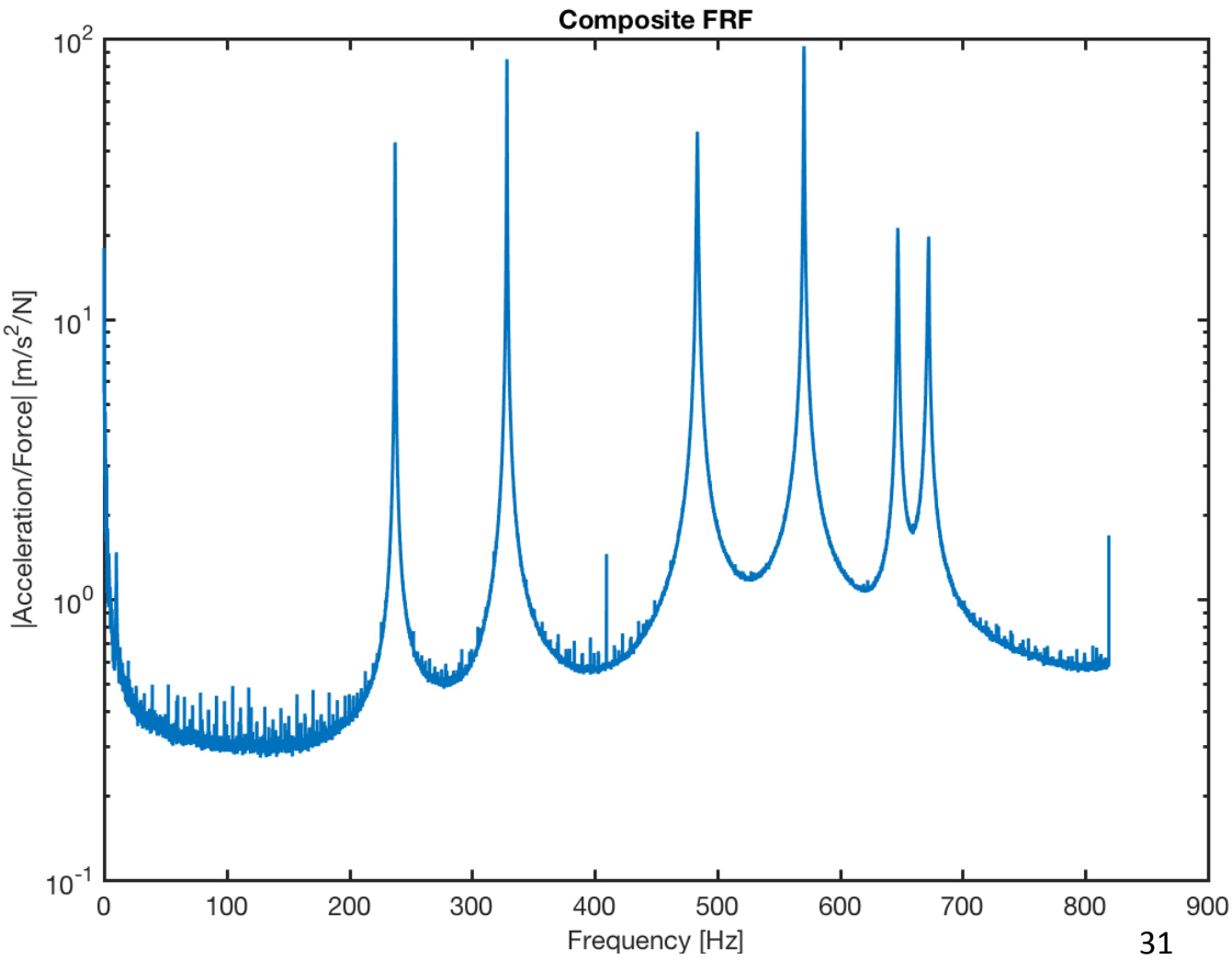
Obtain Mode Shapes



Mode Shapes based on averaged set of measurements with 28 outputs and 7 inputs

Decouple motion

- Convert to modal coordinates using $\ddot{x} = [\Phi]\ddot{\eta}$

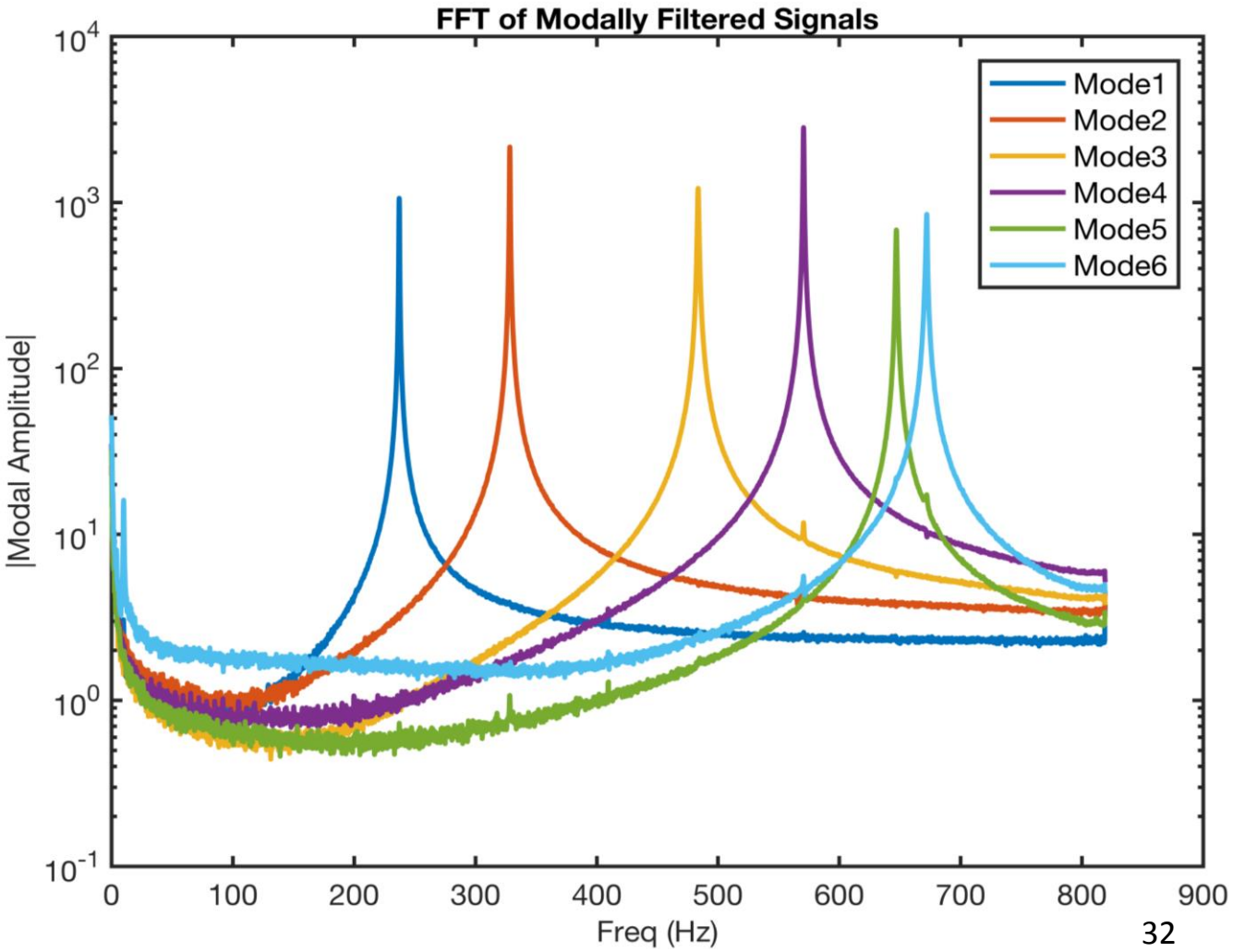


Physical Domain (x)

- 28 accelerometer measurements
- 7 input points
- Coupled motion

Decouple motion

- Convert to modal coordinates using $\ddot{x} = [\Phi]\ddot{\eta}$



Modal Domain (η)

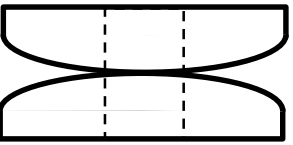
- 6 modes
- 7 input points
- decoupled motion

Hilbert Analysis

- Requires that each response be uncoupled such that it can be represented by a SDOF system
  - Signal can be represented by a decaying harmonic
  - $\ddot{\eta} = Re\left[\exp\left(\psi_1(t) + i\,\psi_2(t)\right)\right]$

- Compute Hilbert Transformation ($\mathcal{H}(t)$) for an amplitude dependent representation of damping and frequency
- $\omega_{d,r} = \frac{d\psi_2}{dt}$
- $\zeta_r \triangleq \frac{d\psi_1}{dt} \Big/ \omega_r$

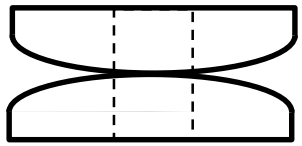
Summary of Hilbert Analysis

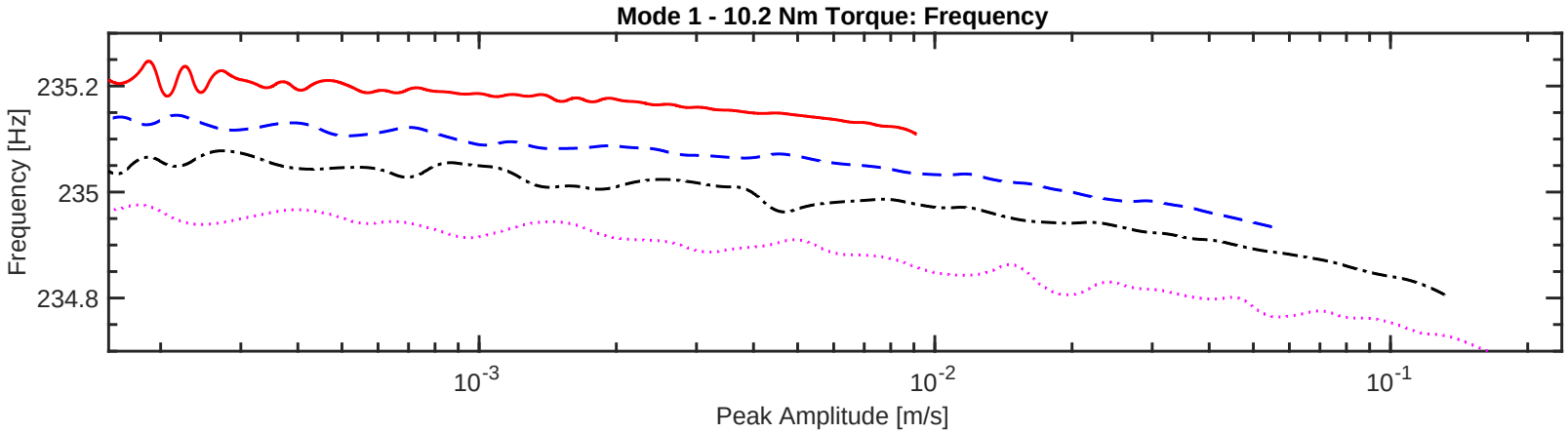


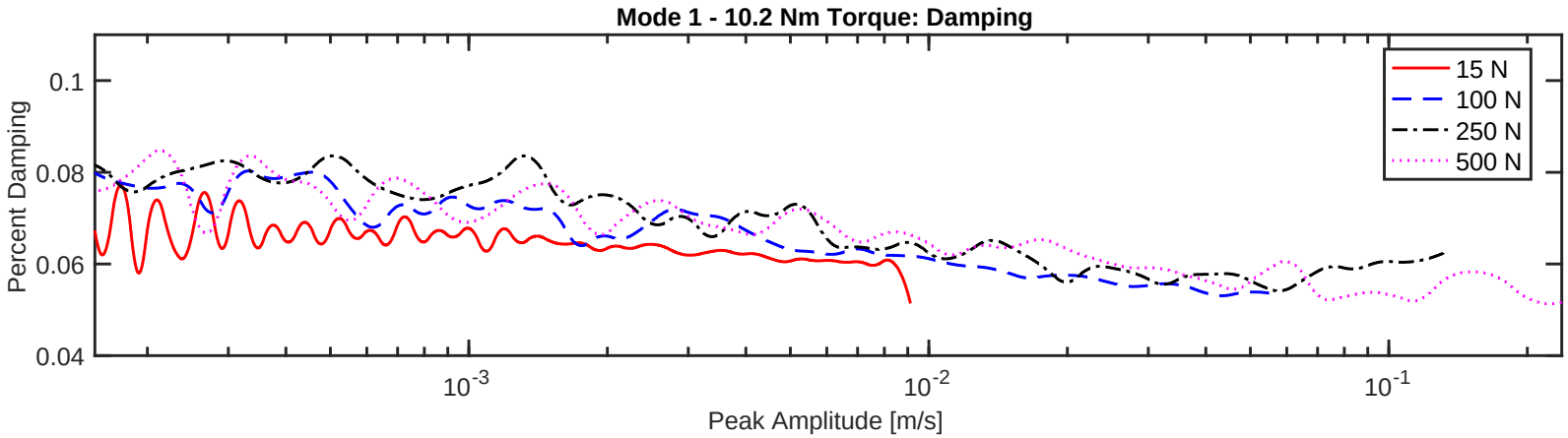
Beam	Mode	Max Frequency Change	Max Damping Change	Comments
B1B2	1	-0.23%	-23.8%	Linear
	2	-0.14%	148%	Damping NL
	6	-1.1%	582%	Damping NL

Beam	Mode	Max Frequency Change	Max Damping Change	Comments
B5B6	1	0.33%	-34%	Linear
	2	0.08%	95%	Small Damping NL
	6	-0.77%	316%	Damping NL

B1B2 – Mode 1 – Force Effect

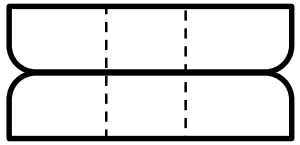


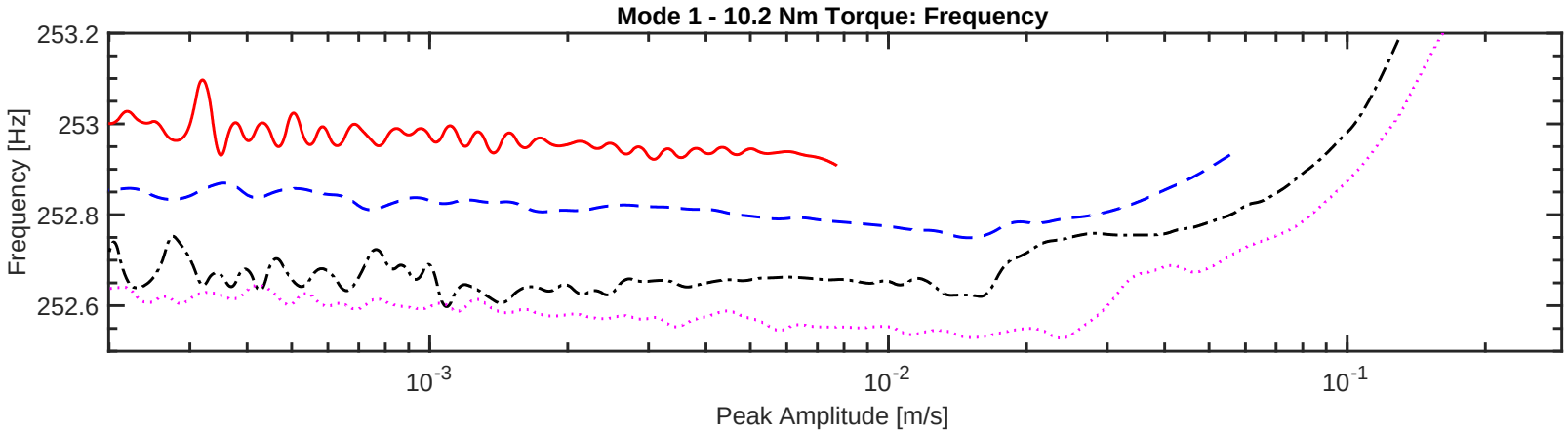


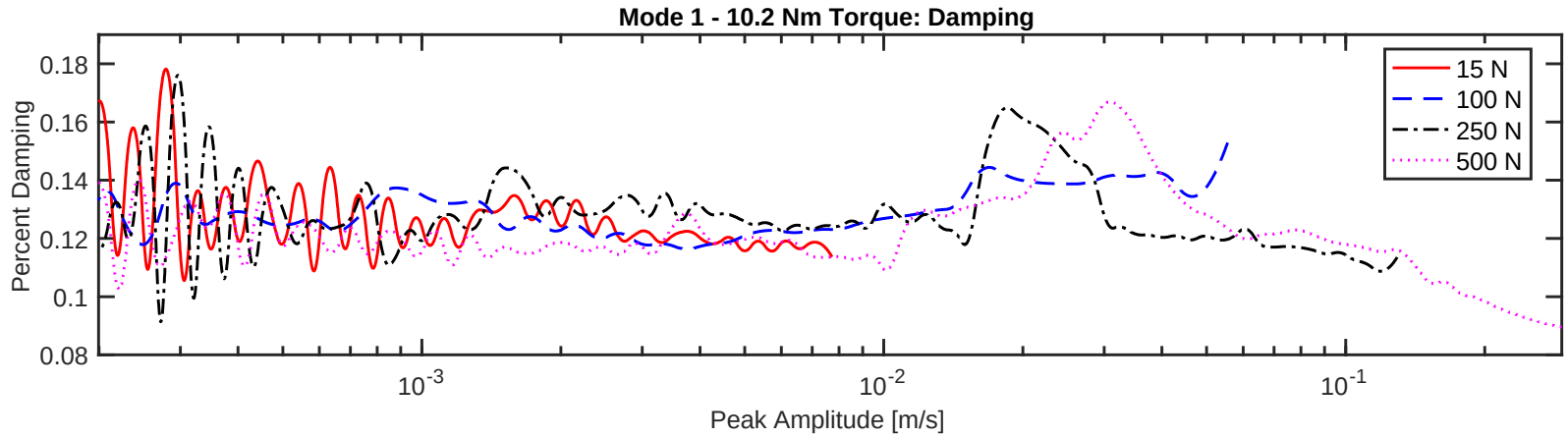


Linear Values		Max Frequency Change	Max Damping Change
235 Hz	0.067	-0.23%	-23.8%

B5B6 – Mode 1 – Force Effect

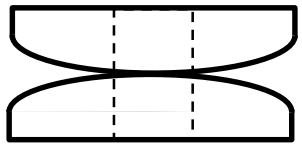


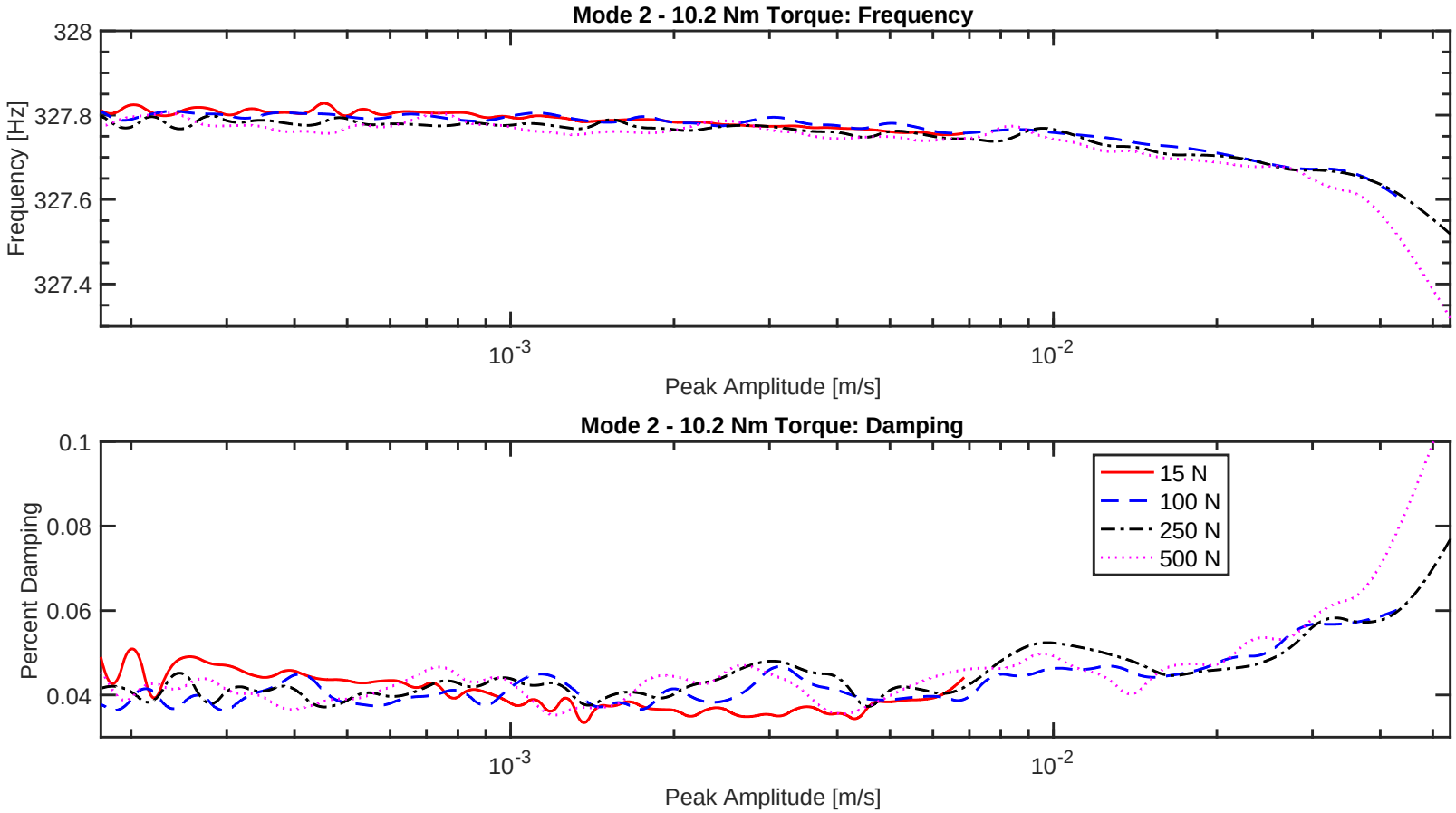




Linear Values		Max Frequency Change	Max Damping Change
253 Hz	0.13	0.33%	-34%

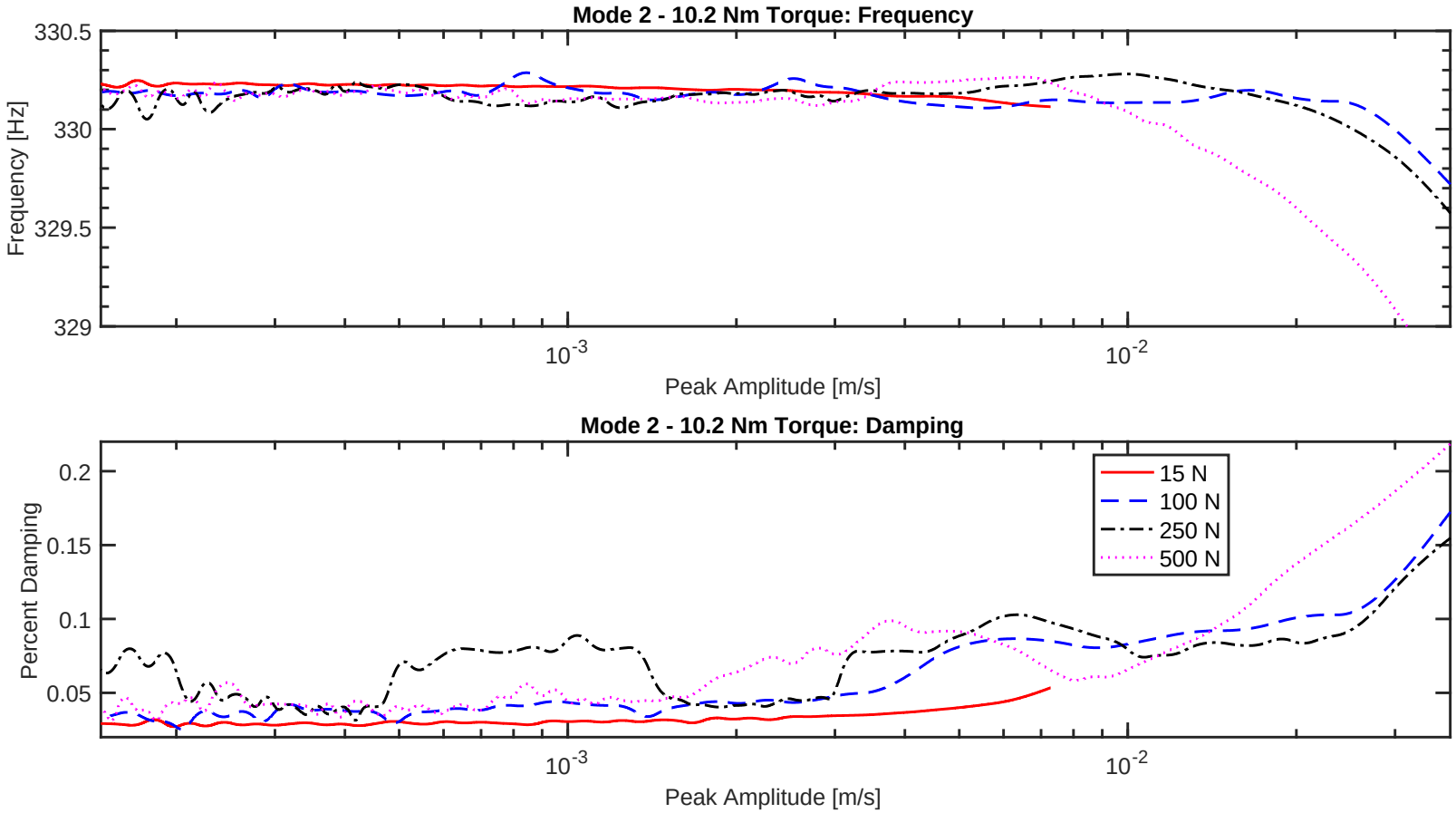
B1B2 – Mode 2 – Force Effect





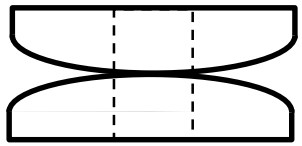
Linear Values		Max Frequency Change	Max Damping Change
328 Hz	0.045	-0.14%	148%

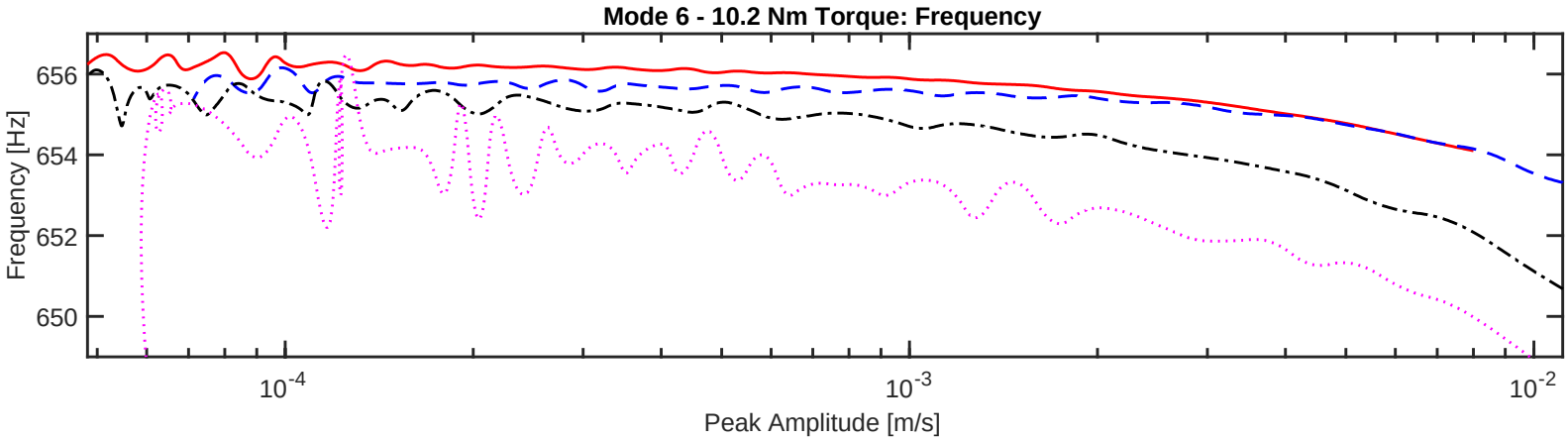
B5B6 – Mode 2 – Force Effect

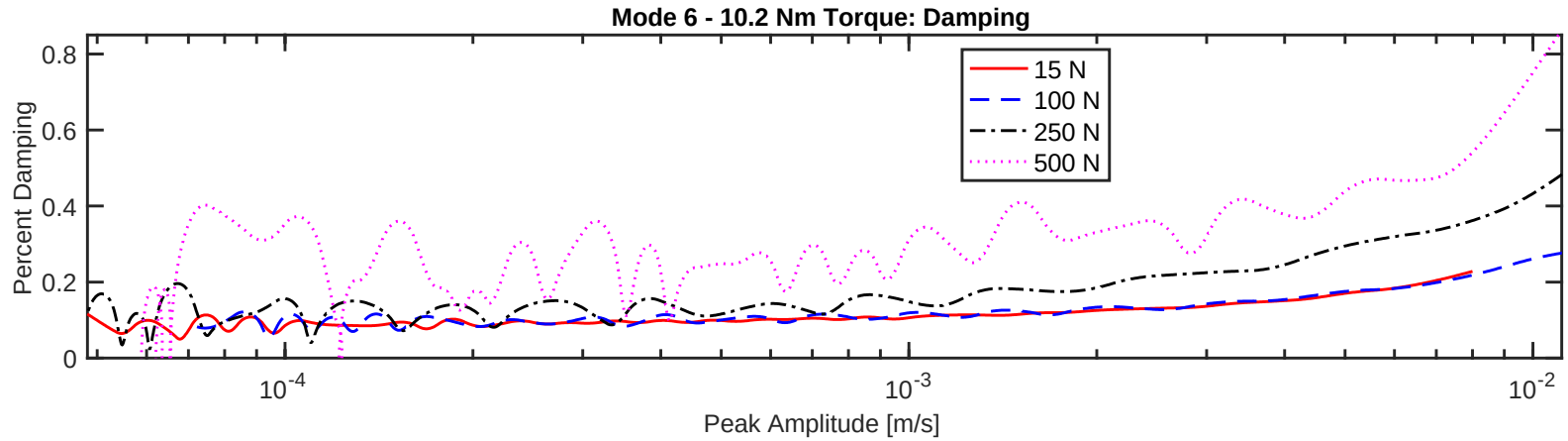


Linear Values		Max Frequency Change	Max Damping Change
330 Hz	0.034	0.08%	95%

B1B2 – Mode 6 – Force Effect

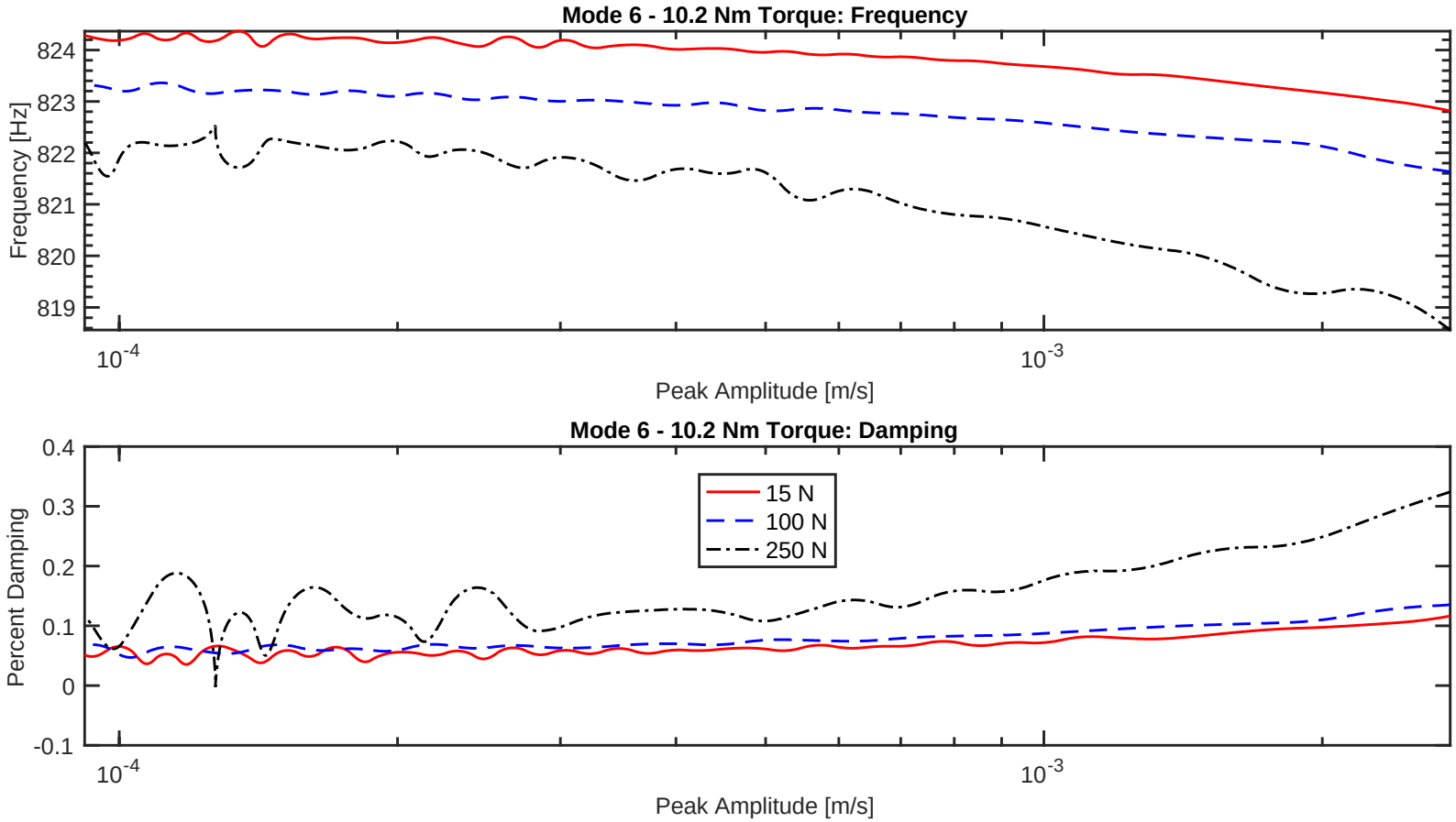






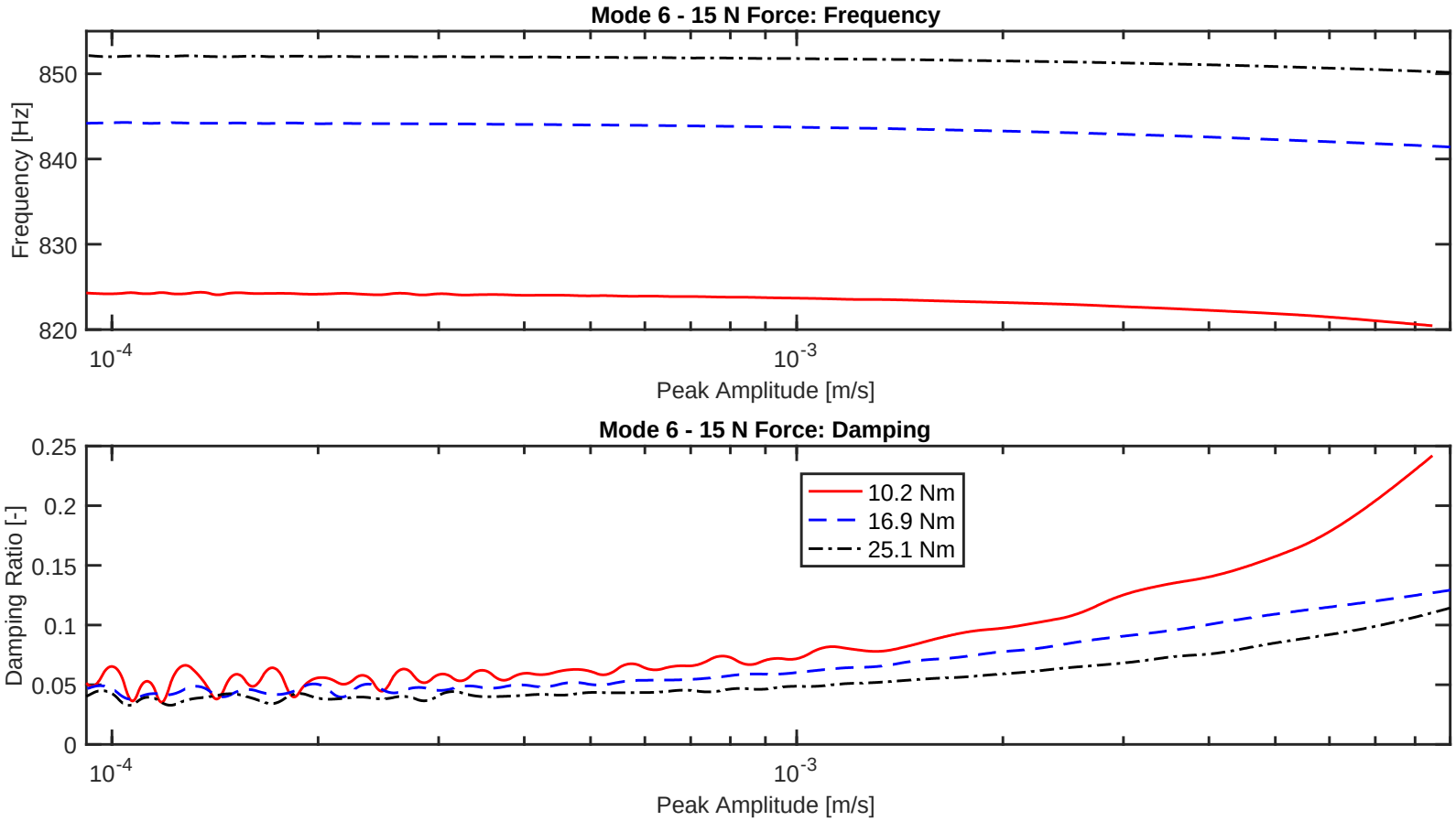
Linear Values		Max Frequency Change	Max Damping Change
656 Hz	0.13	-1.1%	582%

B5B6 – Mode 6 – Force Effect

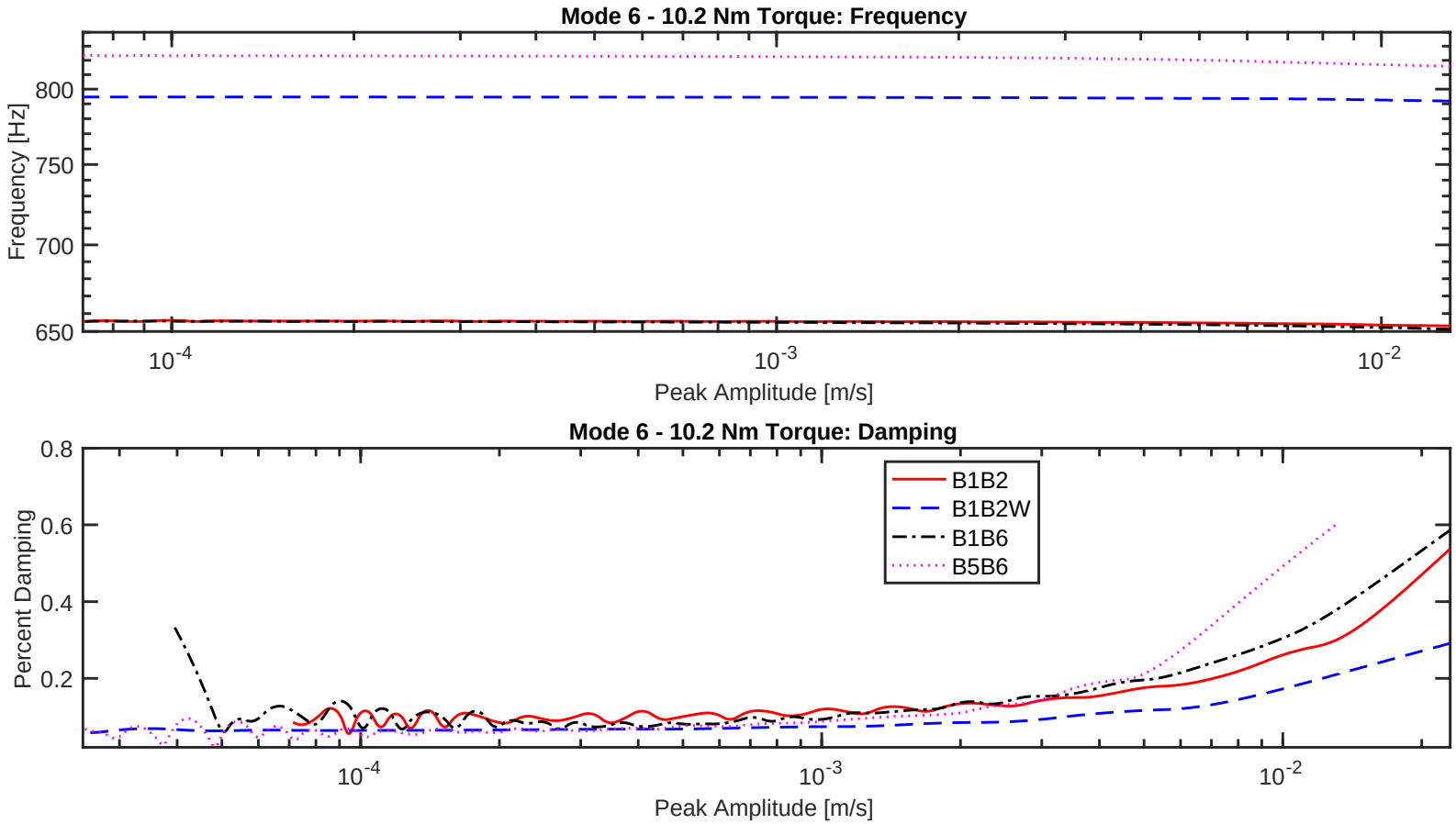


Linear Values		Max Frequency Change	Max Damping Change
823 Hz	0.096	-0.77%	316%

B5B6 – Mode 6 – Torque Effect



Mode 6 (10.2Nm, 100 N) Beam Comparison



Restoring Force Surface (RFS)

- Estimate degree of nonlinearity as a function of polynomials
- Inverse least squares problem
- Equation of Motion:
  - $\ddot{x} + C_1\dot{x} + \cdots + C_N\dot{x}^N + K_1\dot{x} + \cdots + K_N\dot{x}^N = F$
- Methodology:
  - $[Force\ -Acceleration] = [A] * \{coefficients\}$

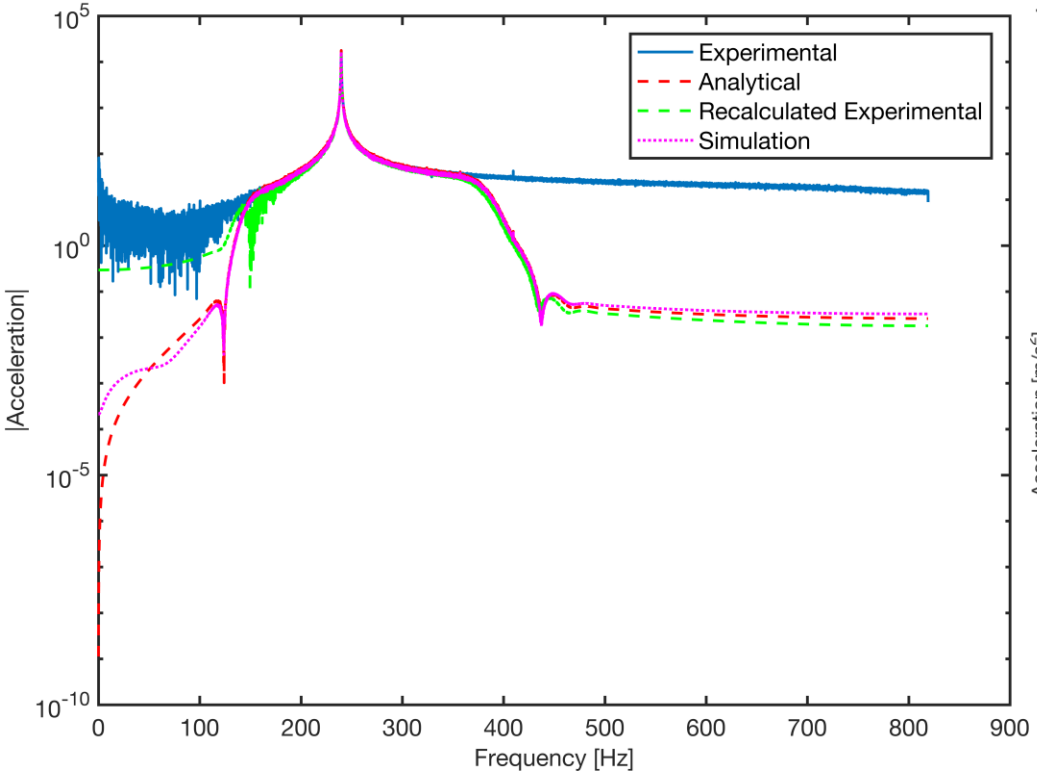
$$[A] = [X(\omega) \ldots X^N(\omega), \mathrm{V}(\omega) \ldots V^N(\omega)]$$

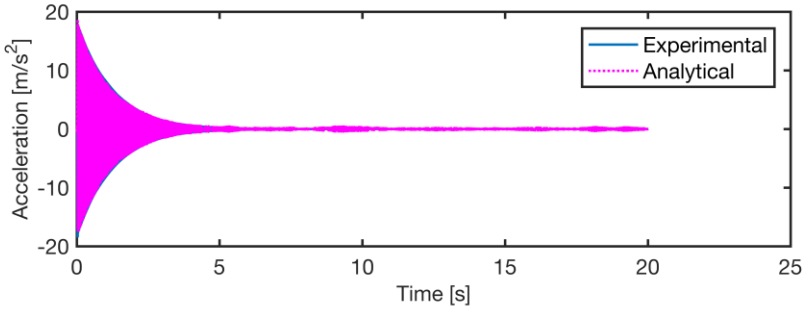
- Problem: Difficulty in capturing degree of damping nonlinearity

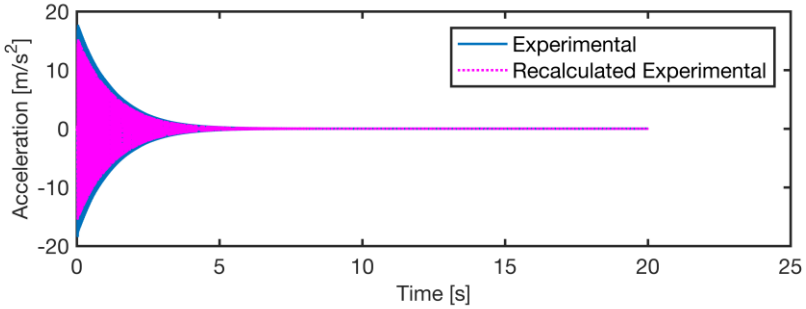
B1B2 Mode 1 – RFS

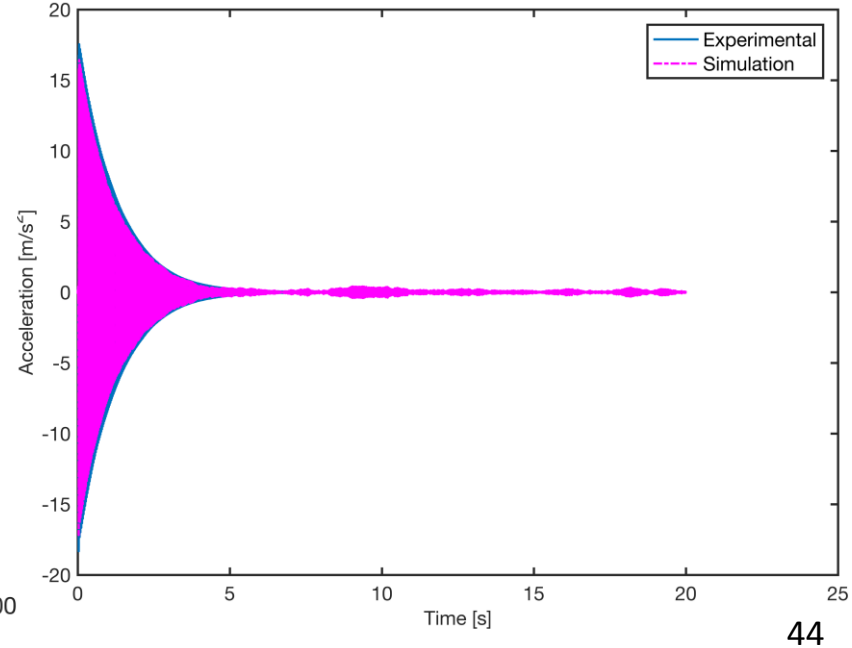
- Cubic damping and stiffness nonlinearities
- Compare against linear solution

$$a_{linear} = -\frac{\omega^2 F}{-\omega^2 + i2\zeta\omega_n + \omega_n^2}$$



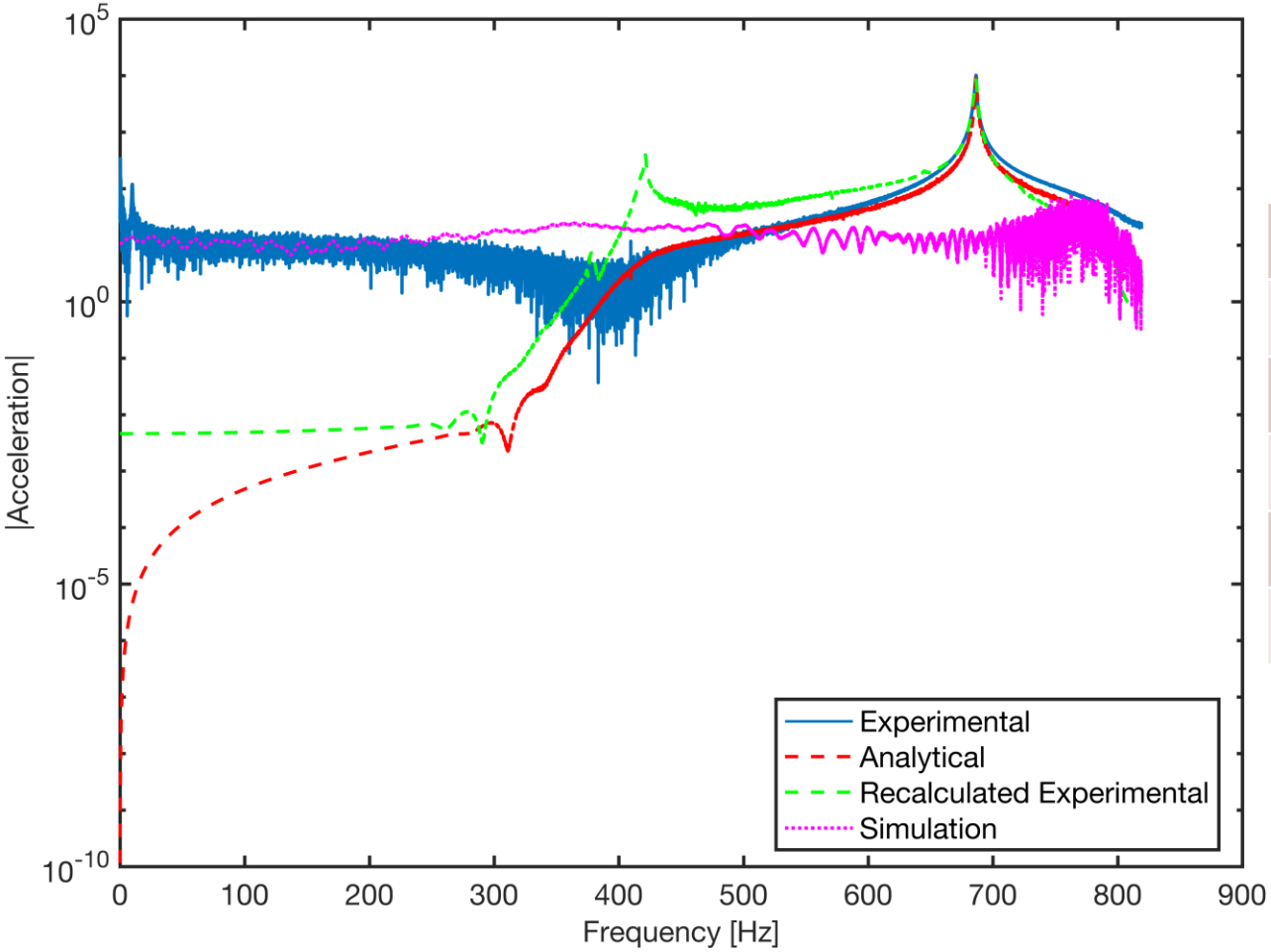






B1B2 Mode 6 – RFS

- Simulation fails due to sensitive parameters
  - Clearly visible in frequency domain



K_1	1.8607e7	N/m
K_2	1.7623e15	N/m^2
K_3	-4.82e21	N/m^3
C_1	6.029	N-s/m
C_2	1.42e5	N-s^2/m^2
C_3	-4.906e7	N-s^3/m^3

Conclusion

- Joints defined by high resolution 3D contour of the contact surfaces and pressure measurements across the interface
- The examined modes exhibit diverse loading conditions at the joints (bending, shearing, clamping)
- A larger contact area between the interface led to stiffer joints and a shift in the structural response to a higher natural frequency
- Increasing the force amplitudes lead to increase in the nonlinearity of the responses

Acknowledgments

- This research was conducted at the 2017 Nonlinear Mechanics and Dynamics Research Institute supported by Sandia National Laboratories.

- Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

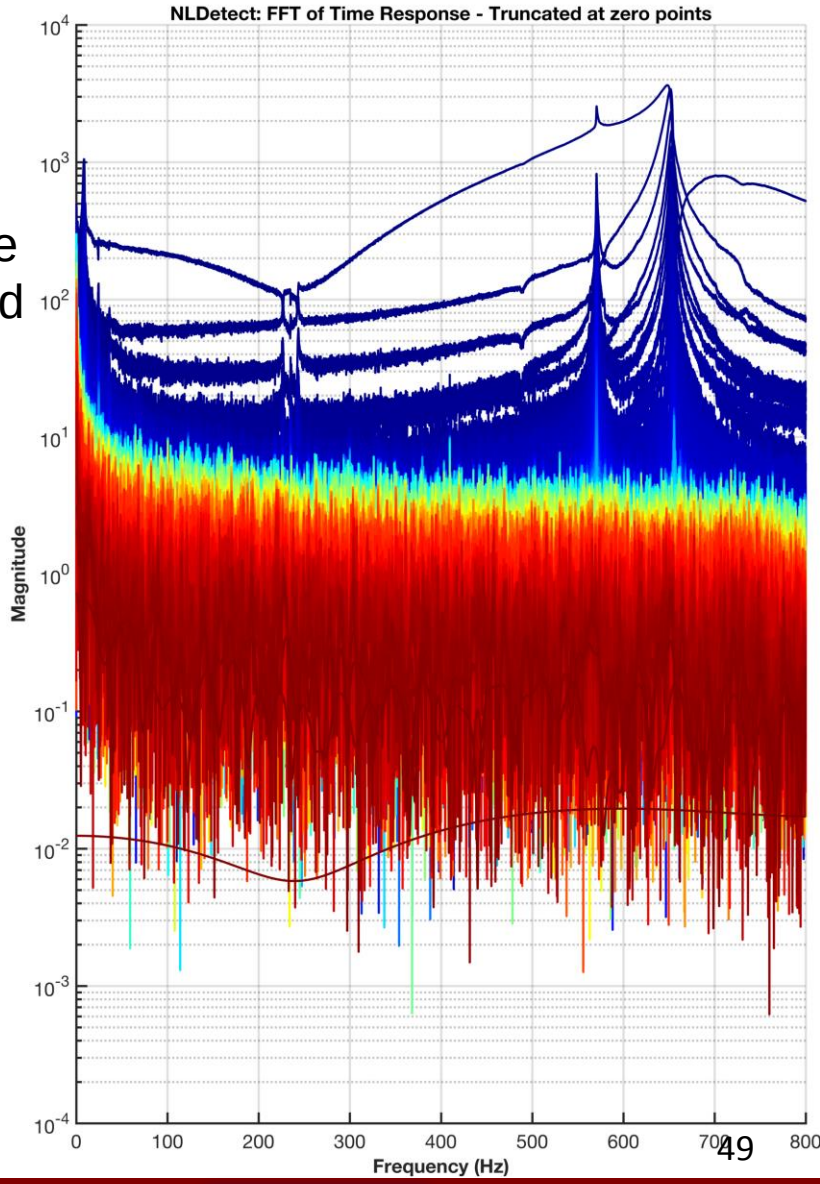
Appendix – Additional Slides

- Additional slides for reference

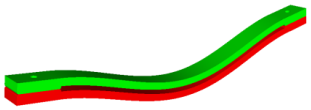
Zeroed Time NL Detection

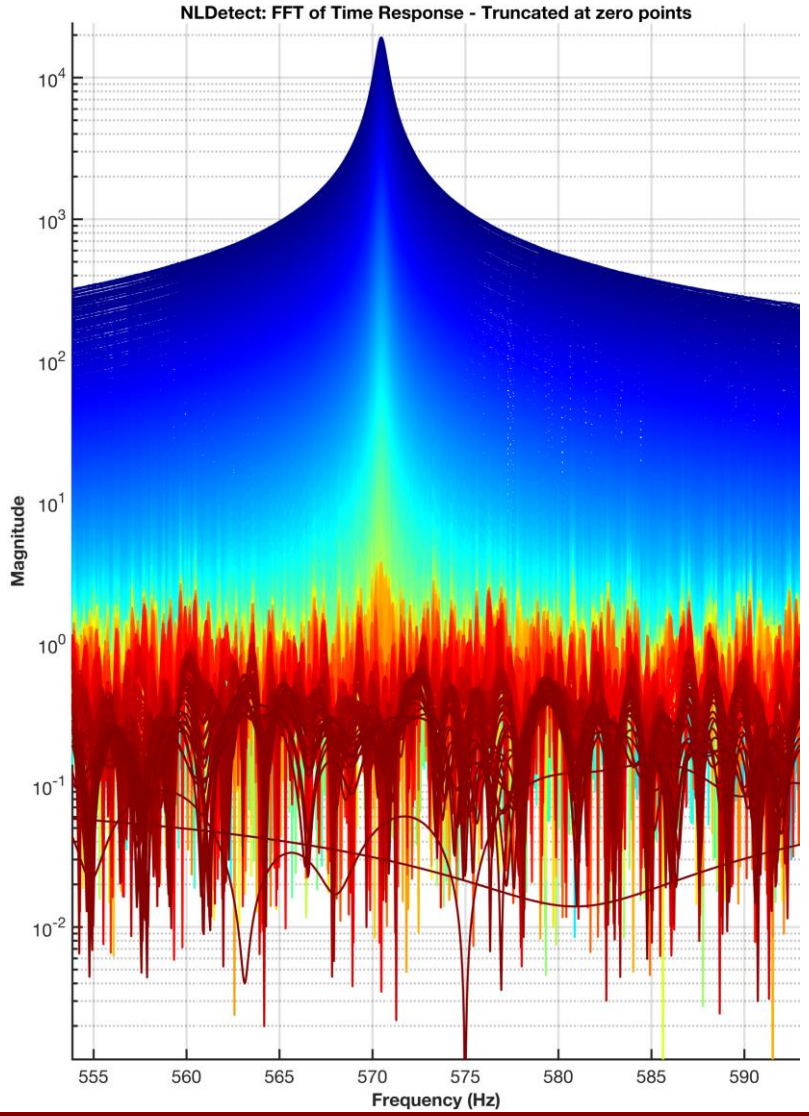
- Method to verify degree of nonlinearity of the modal peak
- Methodology based on Allen and Mayes
  - Zeroes the initial time response at varying intervals
  - Computes the FFT at these varied zeroed time histories

Increase in zeroed time



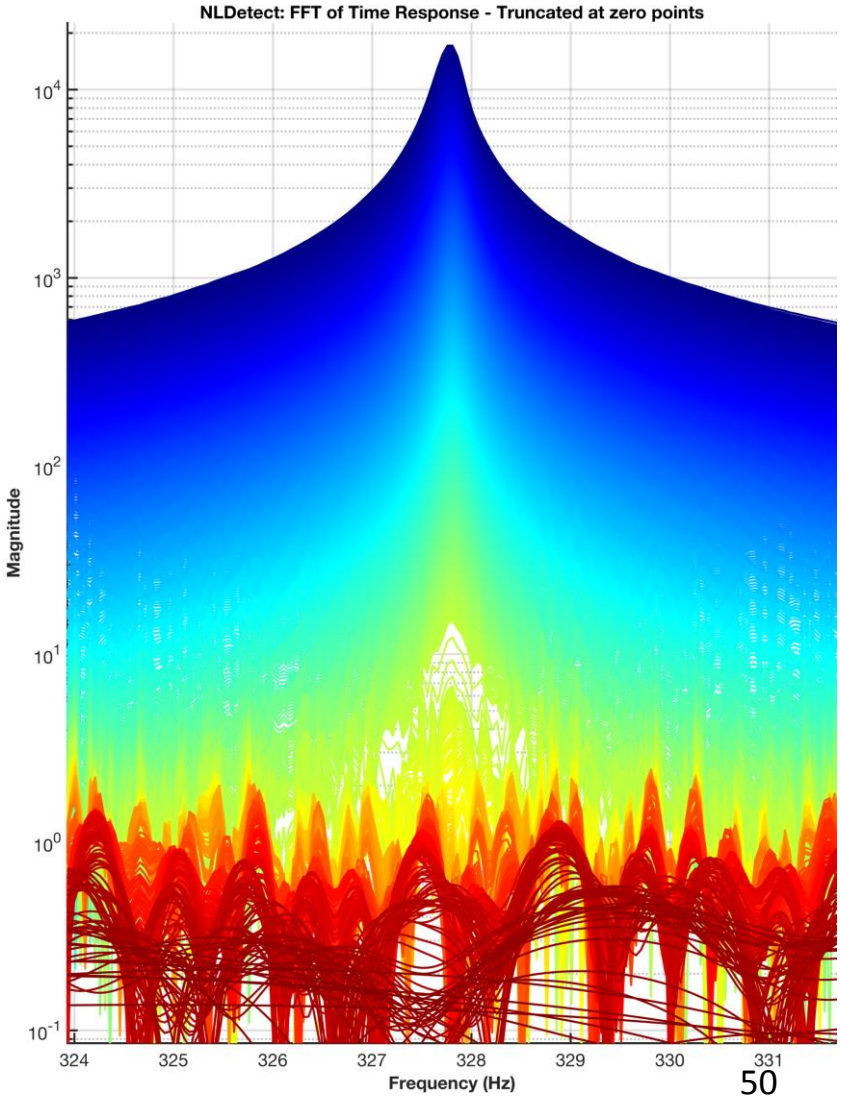
B1B2 – 10.2 Nm – 15N
Mode 1 and 2



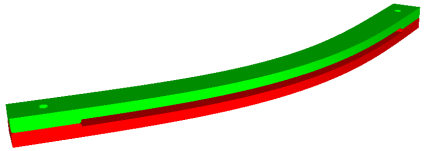


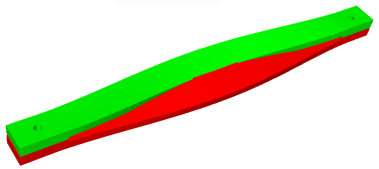
Mode 1

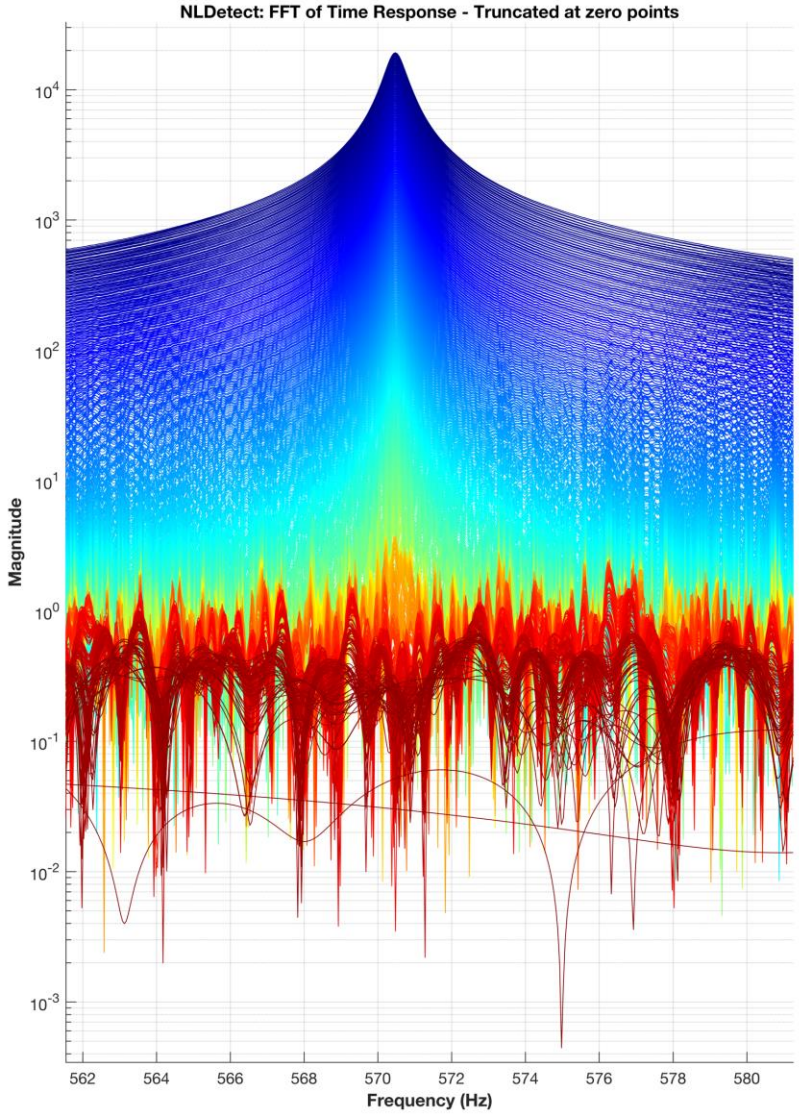
Mode 2



B1B2 – 10.2 Nm – 15N
Mode 4 and 6

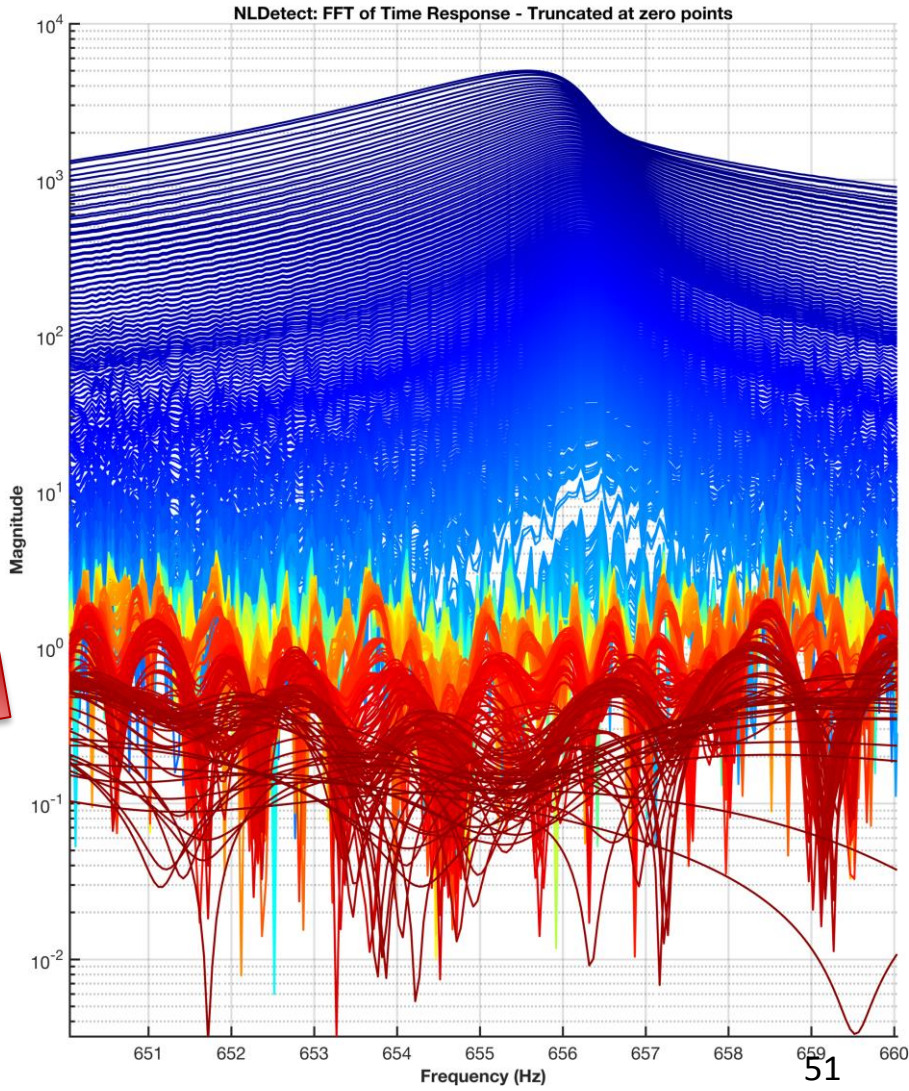




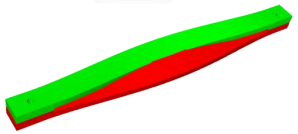


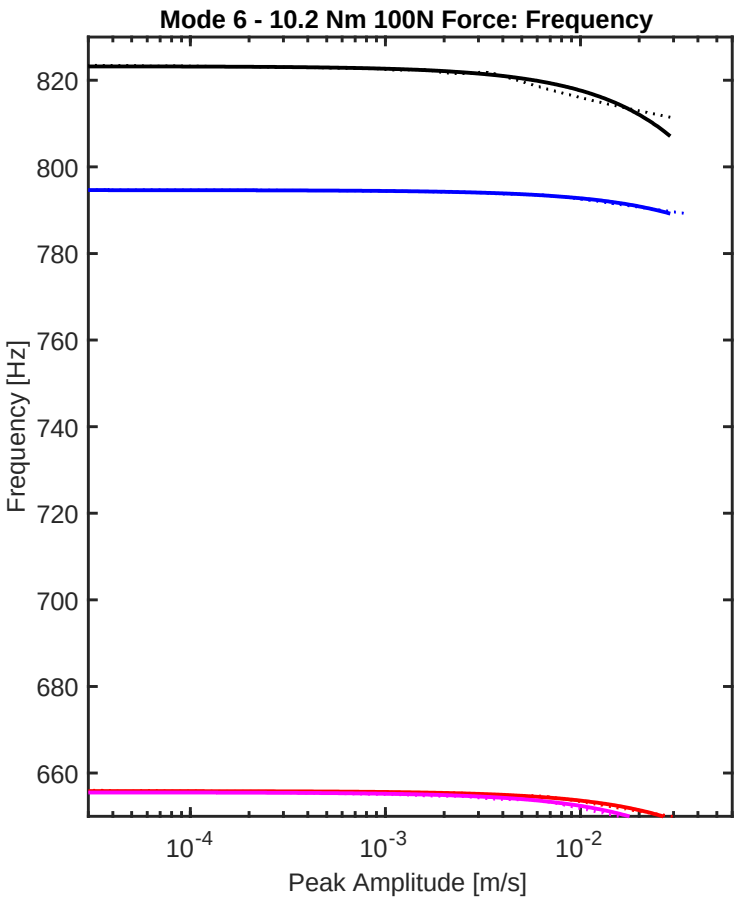
Mode 4

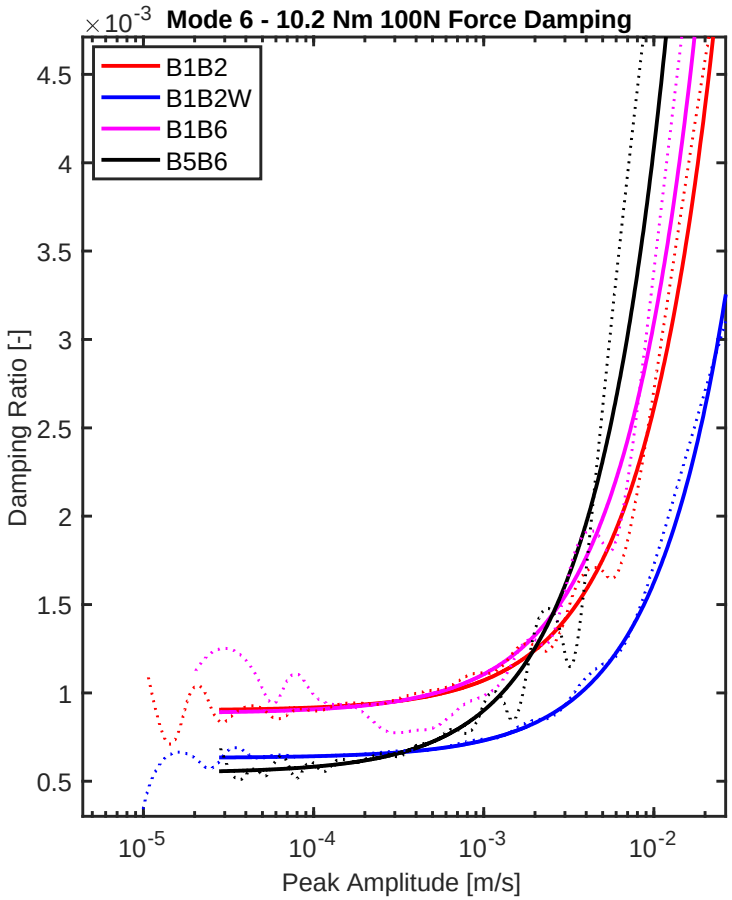
Mode 6



Mode 6 – Beam Comparison



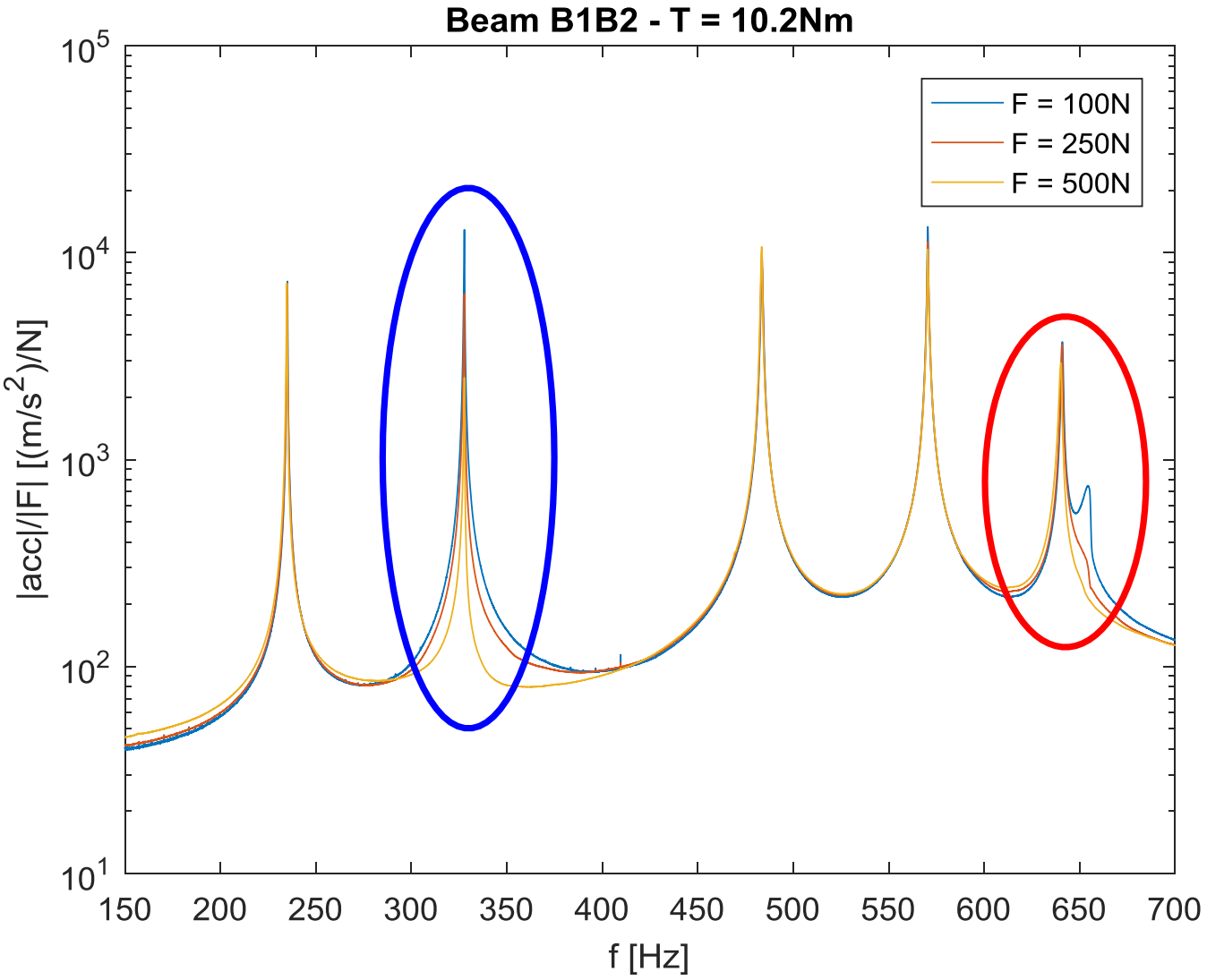




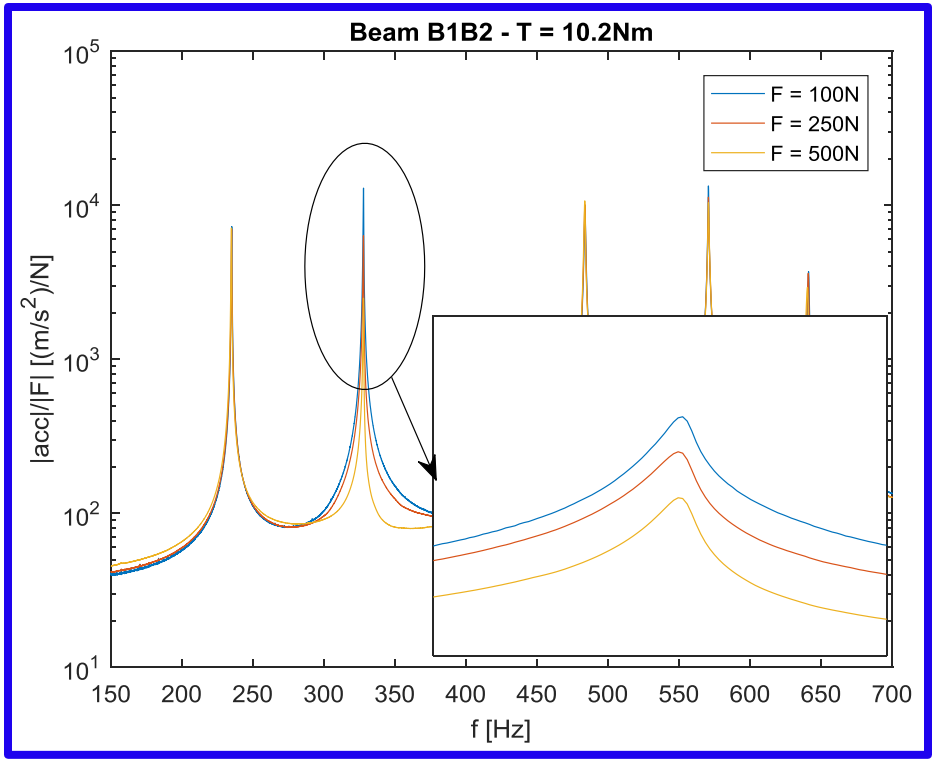
$$\omega_{avg} = 732\ Hz$$

$$\zeta_{avg} = 0.0011$$

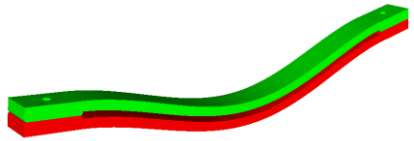
Force Effect

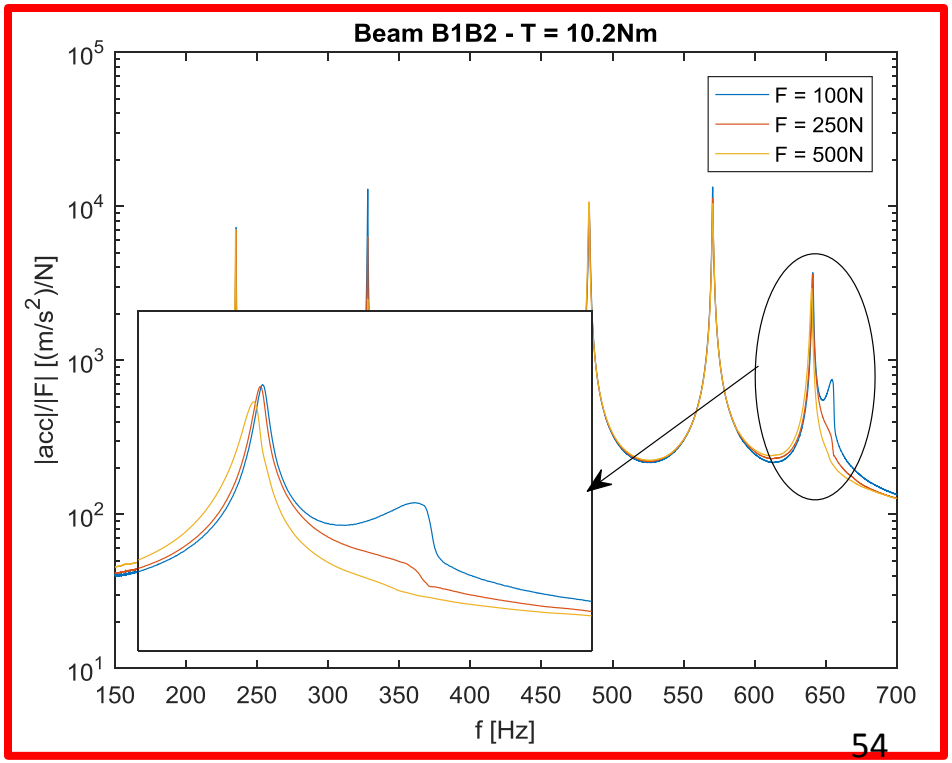


Force Effect



Slight increase in damping for **Mode 2**





Large increase in damping for **Mode 6**